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NUCLEAR EXPLOSIONS - PEACEFUL APPLICATIONS

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February 1969

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OPERATION PRAIRIE FLAT, AIRBLAST PROJECT LN-106, MICROBAROGRAPH MEASUREMENTS, FINAL REPORT: "DISTRIBUTION OF AIRBLAST AMPLITUDES IN THE OZONOSPHERE SOUND RINGS"

Jack W. Reed
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Sandia Laboratories, Albuquerque

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ABSTRACT

Eighteen microbarographs recorded airblast from PRAIRIE FLAT and three 1.2-ton HE blasts. Sensors were spaced at 1- and 2-mile intervals at distances from 119 to 141 miles west of the bursts, to record ozonosphere ducted propagations, hopefully in a caustic.

Results showed that there were humps in the amplitude-versus-distance curve which were observed to pass through the array and changed from shot to shot. These appear to be the caustic, which was broken up by atmospheric irregularities, and resulted in approximately double amplitudes over 6- to 8-mile bands.

Amplitudes were proportional to the 0.425 power of apparent blast yield, which was close to the 0.40 value previously measured.

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Introduction

Description of PRAIRIE FLAT Event

This test explosion[1] was a 500-ton spherical charge of TNT placed tangential to the ground surface. It was fired at the Watching Hill Blast Range of the Defence Research Establishment Suffield (DRES), Alberta, Canada at 1800 Z (1100 MST), August 9, 1968. The burst point was near 50°29.5'N, 110°41'W, and near 2200-foot MSL elevation. It was one of a continuing series of tri-partite (Canada, Great Britain, United States) high-explosives (HE) tests to evaluate airblast, ground shock, and thermal effects of explosions.

Microbarography Objectives

The purpose of this microbarograph (MB) project was to determine the distribution of airblast amplitudes on a sensor separation scale of 1 mile, near the caustic or focus of airblast about 130 miles downwind of the atmospheric circulation at about 150,000-feet MSL altitude. Empirical definition of maximum focused amplitudes and caustic widths are specially needed for comparison with acoustic theory, which predicts infinite overpressures. Data for this ozonosphere-propagated caustic region and sound ring from a large-yield, long-wavelength airblast are required for estimating propagations and damage potentials from Plowshare nuclear explosive excavations.

An added objective was to obtain statistical data quantities of amplitudes propagated from different yields. This would allow an empirical check on the yield-scaling rules which have been derived from unrefracted propagation experiments.

Background

Acoustic ray path calculations show that caustics or foci can be generated by atmospheric sound propagations, where ray density and the resultant pressure amplitudes go to infinity. Physics does not allow this, but a theoretical definition of what really happens has not yet been resolved. Experiments were conducted in 1960 at Nevada Test Site (NTS) with 1.2-ton HE bursts, ducted by jet stream winds near 30,000 feet MSL, resulting in a sound ring at about 30 to 40 miles distance.[2] These tests showed that averaged recorded amplitude magnification was 3.15 and that

the data scatter had a log-normal distribution with a geometric standard deviation factor of about 1.6. Magnification or focus factor, F, was defined as the ratio of recorded amplitude to the calculated amplitude from a yield-scaled standard explosion. This reference explosion has a pressure-versus-distance relation defined by IBM Problem M[3] and an extension to long range that is proportional to the -1.2 power of the distance, that is, $R^{-1.2}$.

Other tests with 1.2-ton HE bursts separated by 2- to 9-minute intervals showed that waves ducted by the ozonosphere near 150,000 feet MSL were not particularly repeatable.[4] The geometric standard deviation factor for changes on this short time scale was near 1.5.

It was believed that longer wavelengths, from larger yield explosive sources, should be less scattered by atmospheric irregularities and that both time and space variations in amplitude would show smaller geometric standard deviations. Space and time variations were to be recorded by this MB project for both PRAIRIE FLAT 500-ton HE yield and for three 1.2-ton HE blasts.

Experimental Plan

Microbarograph Array

Eighteen microbarograph sensors were located on a line west from PRAIRIE FLAT at distances from 119 to 141 miles, as shown in Figure 1. This flat farm region has roads on nearly every section line, and there was a good gravel farm road with little traffic nearly straight west from PRAIRIE FLAT ground zero (GZ). Elevation along the array varied only from 3125 to 3300 feet MSL. Station locations were not surveyed, but it was assumed that cross-roads on section lines were exactly 1 mile apart, and stations were located accordingly. It turned out, from wave arrival times, that this assumption was adequate for project purposes.

Six camper-truck recording stations were placed 4 miles apart along the road. Each truck housed recorders for three sensors, one at the truck site, and two at the ends of mile-long cables laid east and west from the truck. The array is shown in Figure 2.

Propagations from high-altitude ducting were expected to be maximized at these distances toward the west and downwind of the easterly wind circulation which is found in summer at temperature latitudes. (Winter-time propagation would have been maximized toward the east with upper westerly winds. In equatorial and polar latitudes the circulation patterns are more complicated.)

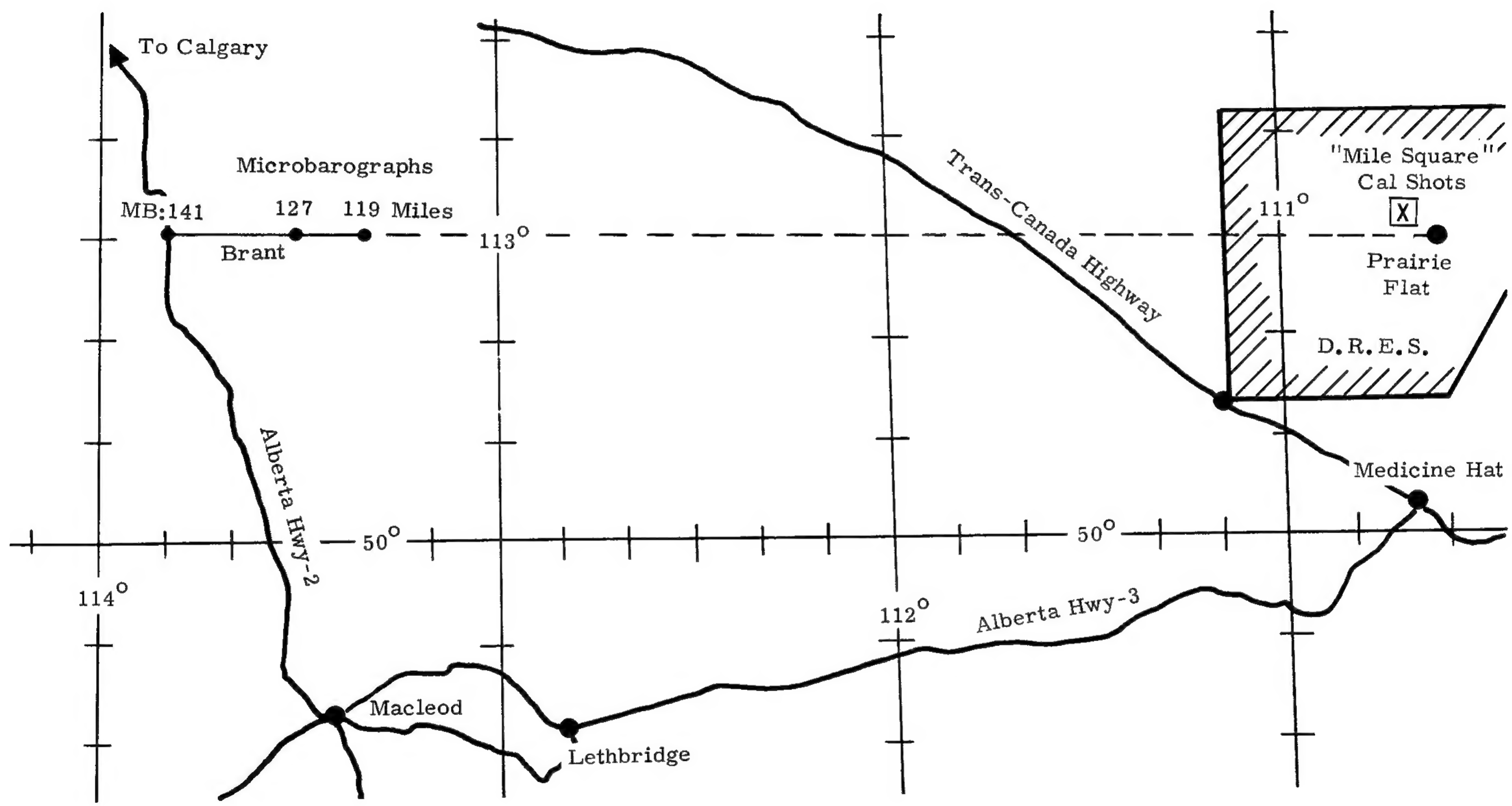

Figure 1. Map of Microbarograph Project Locations

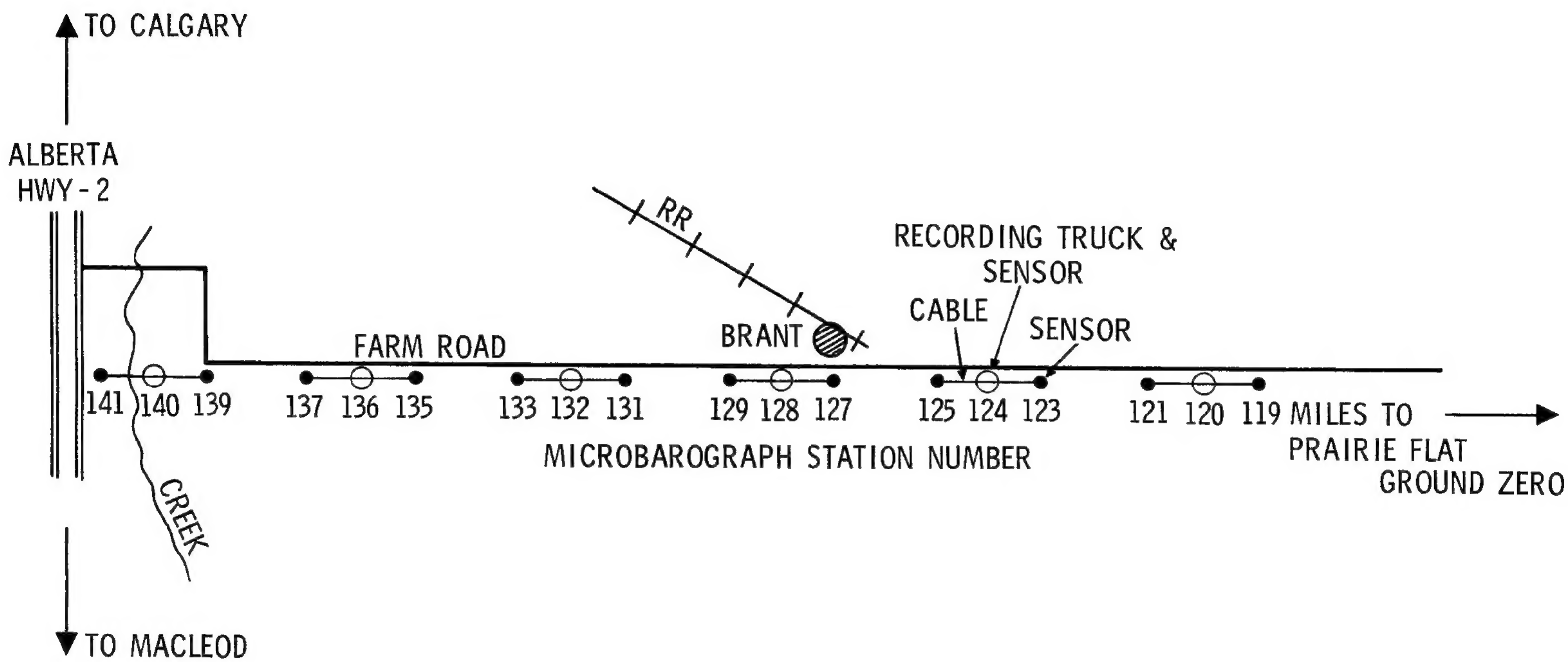

Figure 2. Detail Map of Microbarograph Array

Each microbarograph consisted of a twisted bourdon tube aneroid barometer sensor with electronic detector and amplifying components which have been used for many years in nuclear test measurement.[5] Range switching allows measurements from 0.5 microbar (μb) to 96-millibar (1 psi = 69 mb) amplitudes with about ±20-percent accuracy and repeatability. Recording was on Brush pen and paper recorders operated at 1-inch-per-second paper speed. Each signal was recorded by two pens set at different attenuations so that expected signals would nearly fill one channel graph width and a four-times larger signal would fill the other channel limit. This equipment has a frequency band-pass extending from about 30 cycles per second to 20 seconds per cycle, giving full response to all significant acoustic signals expected.

Each sensor was protected from wind noise by a ring of snow fence of 10-foot radius, which reduces ambient noise by about a factor of six, as shown by Bodhaine.[6]

Project control was by radio from a van located at the PRAIRIE FLAT official observing point. Countdowns were relayed by VHF radio to the calibration shot firing party at "Mile Square," 1800 feet from the line of small calibration shots. These shots were fired by manual switching since there was no need for great timing precision. Countdowns were also relayed by HF single-sideband radio to an MB radio center near Brant and subsequently by point-to-point VHF radio to each MB recording truck.

Calibration Shots

Three small HE bursts were fired to give a comparison of space variability at different wave frequencies from different yield sources. If small-scale atmospheric structure caused most of the observed propagation variability for small yields, this variability might be ignored to some degree by longer wavelengths. Variability in time had been tested elsewhere but an addition to the stock of statistics probably has some value. The cost of these added data, on both time and space variability, was relatively small since the major cost of placing the MB measuring equipment was committed for the main event.

These "calibration shots" (this name has been acquired from their use in estimating muffling or transmission factors for large underground bursts) further allowed comparison of averaged amplitudes to check the assumed yield-scaling relationships.

These so-called calibration shots, which consisted of 1.2 tons of HE (TNT) on 15-foot wooden platforms, were burst at Z minus 30 minutes, Z minus 15 minutes, and Z plus 15 minutes. The firing area was about 5 miles north from PRAIRIE FLAT, at "Mile Square" in Figure 1, giving about the same distance range to the MB array. Above-ground bursts were used to increase the apparent source strength through height-of-burst effects and to minimize some unrepeatable cratering and detonation effects of small near-surface HE bursts.

Meteorological Data

Atmospheric measurements were obtained by DRES for use in evaluating the recorded propagations.[7] These consisted of temperature and wind soundings by rawinsonde balloon to nearly 66,000 feet MSL at shot time. Higher altitude data to over 180,000 feet MSL were obtained by an Arcas rocketsonde launched at Cold Bay, about 300 miles north of DRES.

Calculations

Atmospheric acoustic ray path calculations for explosions have been described by Cox,[8] and Cox, Plagge, and Reed.[9] They are made from upper-air weather data inputs by a digital computer program at Sandia Laboratories. Calculations for wave refraction in a stratified windy atmosphere, derived by Thompson,[10] were used as standard practice for blast safety predictions. The calculation output is a set of coordinates showing the travel of a ray path bending away through the various atmospheric layers and returning to ground in a sound ring distant from the source. This program also gives wave arrival time at each located point along the ray path for comparison with arrival recordings. Finally, a relative amplitude "focus factor" is obtained from the ray convergence and is applied to a standard explosion wave prediction to give an overpressure or amplitude prediction.

Predictions

The PRAIRIE FLAT explosive was designed to simulate the airblast, cratering, and ground shock from a 1-kt nuclear explosive (NE) surface burst.[1] This was expected to be the airblast-generating equivalent to a 1.6-kt NE free-air burst. Scaling the standard overpressure-distance curve of IBM Problem M (1-kt NE free-air burst at sea level with p = 1000-mb ambient pressure)[3] gives expected curves for operation PRAIRIE FLAT, as shown in Figure 3. Close-in overpressures, Curve 1, were computed for ambient atmospheric pressure, p = 936 mb, near 2165 feet MSL. Distant peak-to-peak pressure amplitudes, Curve 2, were computed for p = 901 mb, near 3200 feet MSL. Curve 3 shows standard recorded amplitudes from calibration shots, based on an apparent yield equivalent of $W_a = 4.26$ t NE. This results from doubling 1.2 t HE to obtain 2.4 t NE equivalence, and multiplying by 1.77 for the height-of-burst effect, as determined from data collected by Vortman and Shreve.[11]

Beyond the end of calculations in IBM Problem M, past $R_M = 9000$ feet, $\Delta p_M = 0.37$ psi, the assumed decay follows $\Delta p \sim R^{-1.2}$, as was found by empirical observation of unrefracted propagations from high-altitude HE bursts in Project BANSHEE.[12] Peak-to-peak recorded amplitude, $p_K{}^*$, is obtained by multiplying incident overpressure by 1.35, from IBM Problem M,[3] to give amplitude, and then doubling for ground reflection at long ranges and significant incident angles.

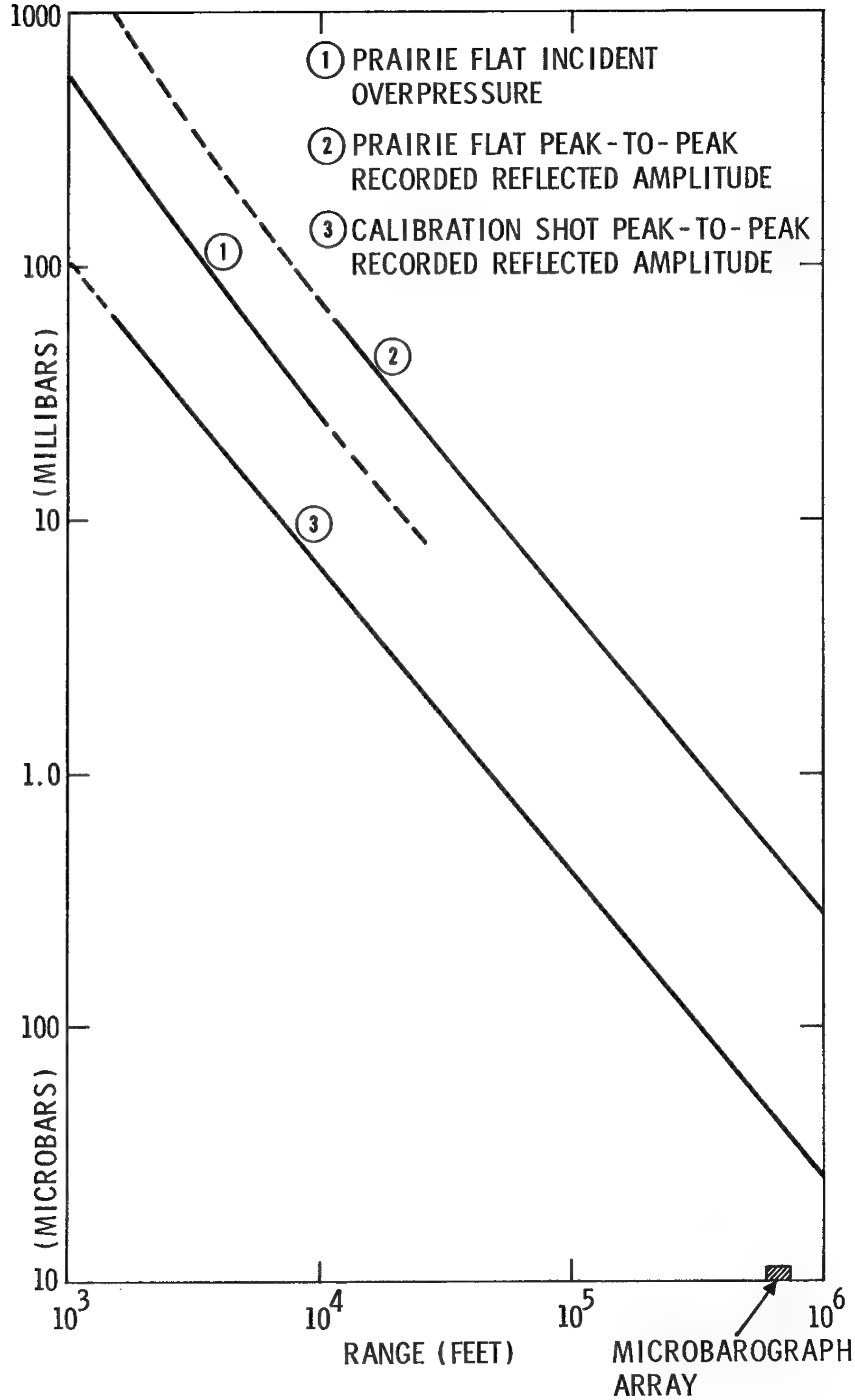

Figure 3. Standard Pressure-Distance Curves for Explosions

Explosion amplitudes recorded in the ozonosphere sound ring, near 135-mile ranges, from many HE and NE events, occasionally give more than double the standard values. Microbarographs were therefore operated with set ranges to contain $p_K{}^* = 80$ and $320\ \mu b$ on the two channels from calibration shots. A set range for $p_K{}^* = 2.4$ and 9.6 mb from PRAIRIE FLAT was used to give an added safety factor in case the magnification potential increased with increased yield, in accordance with some theories.

Arrival times were estimated from Nevada experience with group velocities near 950 ± 25 feet per second (290 meters/second). These ranged from 670 seconds at MB-120 to 755 seconds at MB-140.

Infrasonic Acoustic Detection at Washington State University

Arrangements were made to assure that the infrasonic acoustic wave detection apparatus at Washington State University, Pullman, Washington, was operating at the correct time and attenuator settings. Coordination was with Professor Lloyd B. Craine, Washington State University, and Professor Joe Thomas, University of Idaho, who cooperate in this station operation. At Pullman, 2110-kft (400 mi.) distance, predictions were for 15- and 130-μb amplitudes from the two yields, and 36-minute travel times. Shot-to-station bearing was 227 degrees True (clockwise from True North). The pass-band for this equipment is from 0.45- to 60-second periods.[13] Their array consists of four microphone sensors located at the corners of a 5-mile square centered on the city.

Results

Explosions*

The three HE calibration shots were fired on schedule with all indications of high-order detonation. Each started grass fires, but the fire-fighting preparations of blading circular containment zones and having stand-by fire-fighters proved adequate. Fires were brought under control and extinguished within about an hour.

There was no exact timing record made of these bursts, but MB-recorded wave arrivals indicated that all fire times were within 1 second of schedule. Operations by the contractor, Integrated Velocity Services, Ltd., of Calgary, on these calibration shots were entirely satisfactory.

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*The preliminary report on PRAIRIE FLAT[14] will have exact event times and some close-in blast data to determine whether the 1.6-kt NE yield equivalence was justified. This report should be distributed in the very near future.

Weather Conditions

Weather data were furnished by Mr. Ollie Johnson, Head, Meteorology Section, DRES, and are reproduced in Table I.[7] A balloon-borne rawinsonde instrument gave wind and temperature data to 66,000 feet MSL. Data for higher altitudes were obtained from an Arcasonde rocket observation made at Cold Lake, Alberta. At P-F time skies were nearly clear at DRES and surface winds were light and variable.

At the MB array there was a low stratus overcast and temperatures were near 50°F (10°C, sound speed 1100 ft/sec). There were only occasional light local winds during the wave recording period, so background noise was generally very low.

Temperatures and winds aloft were used to calculate the sound velocity versus altitude structure toward bearings of 270 degrees (MB array) and 227 degrees (Pullman, Washington), as shown in Figure 4. The sound-speed curve is also shown to give an impression of the wind effect.

As will be described later in this report, MB records were used to interpret sound velocity points which have been added. Also a "fabricated" structure is shown, which was generated to better explain observed propagations, and was made up by assuming 20 ft/sec wind errors at intermediate levels between rocket reports.

Microbarograph Records

All MB recordings are reproduced in Figures 5, 6, 7, and 8, aligned so that first arrivals at each station are nearly on a vertical line for reference. The first and second calibration shots gave clear records of four distinct wave group arrivals. The fourth group had disappeared by the time of the third calibration shot. The larger yield of PRAIRIE FLAT, as shown in Figure 7, gave more detectable waves which were too small to correlate easily with calibration shot records. These record reproductions have not been corrected for actual instrument calibration; only the nominal set range scale is shown. They do, however, show how wave patterns drift through the time and space matrix of this experiment.

Corrected values of wave amplitudes are listed in Tables II, III, IV, and V, for detailed comparison. Amplitudes were uniformly defined from peak-to-trough for comparison purposes. Occasional remarks of primed wave identifiers show where the subsequent trough-to-peak amplitudes happened to be greater. In Table IV the sharp spikes of a few recordings are reported in remarks.

The early part of the record of CAL-1 at Station 133 was approximately reconstructed from a recording which was temporarily out of limits because of power problems, so that accurate amplitudes for Signals A and B could not be reported in Table II.

TABLE I

Upper Atmospheric Wind Temperature and Sound Data*

Height (ft)	Wind Direction (deg)**	Wind Speed (ft/sec)	Temperature (deg C)
0	180	0	19.8
532	180	0	17.7
1584	132	5	14.6
2815	82	8	10.6
4523	177	8	5.2
7419	91	25	2.2
10320	109	33	-3.3
12976	102	47	-3.6
15023	100	65	-7.5
18235	99	94	-12.8
21731	96	101	-20.1
24811	92	121	-25.4
27318	91	162	-28.0
30211	88	148	-34.0
33850	86	167	-42.1
36694	83	182	-48.4
39184	92	133	-52.6
42013	95	101	-54.5
47527	86	74	-56.0
52914	118	45	-57.6
56362	108	28	-55.0
61631	203	8	-52.9
63452	190	16	-50.9
70014	210	23	-47.9
76576	260	15	-44.9
83138	270	18	-42.0
89700	290	15	-41.9
96262	260	18	-35.9
102824	270	27	-31.9
109386	280	28	-28.9
115948	270	32	-23.9
122510	280	50	-17.9
129072	290	50	-13.9
135634	290	37	-8.9
142196	280	37	-5.9
148758	280	62	-4.9
155320	280	74	0.0
161882	290	72	5.9
168444	290	67	3.9
175006	290	96	2.9
181568	280	131	-1.0

*DRES Rawinsonde Data to 66,000 feet MSL, balloon released at 1100 MST, August 9, 1968. Data above that from Arcasonde rocket launched at Cold Lake, Alberta, soon after P-F confirmation.

**Wind direction is the direction toward which the wind is blowing.

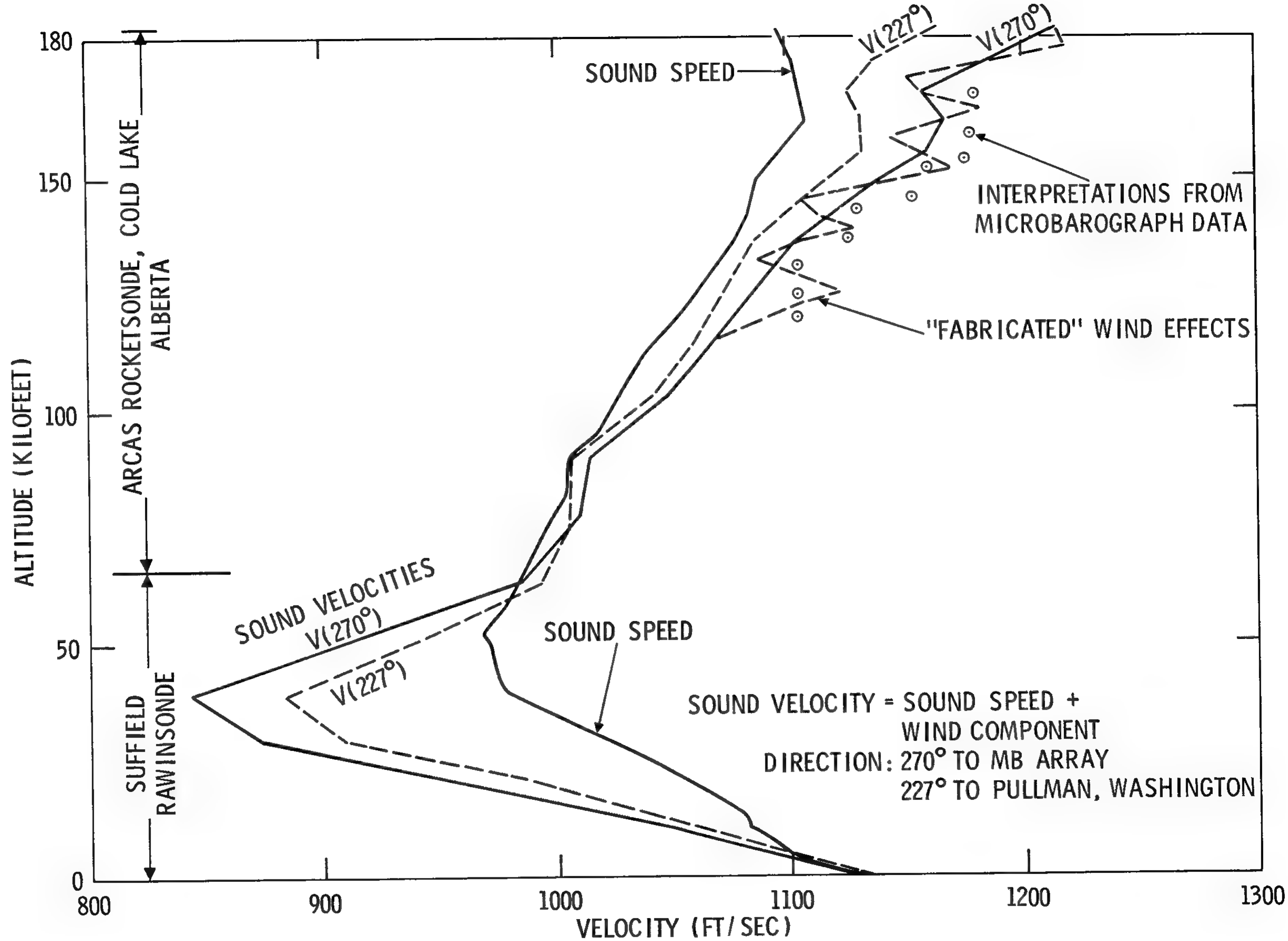

Figure 4. PRAIRIE FLAT Sound Velocity Structures

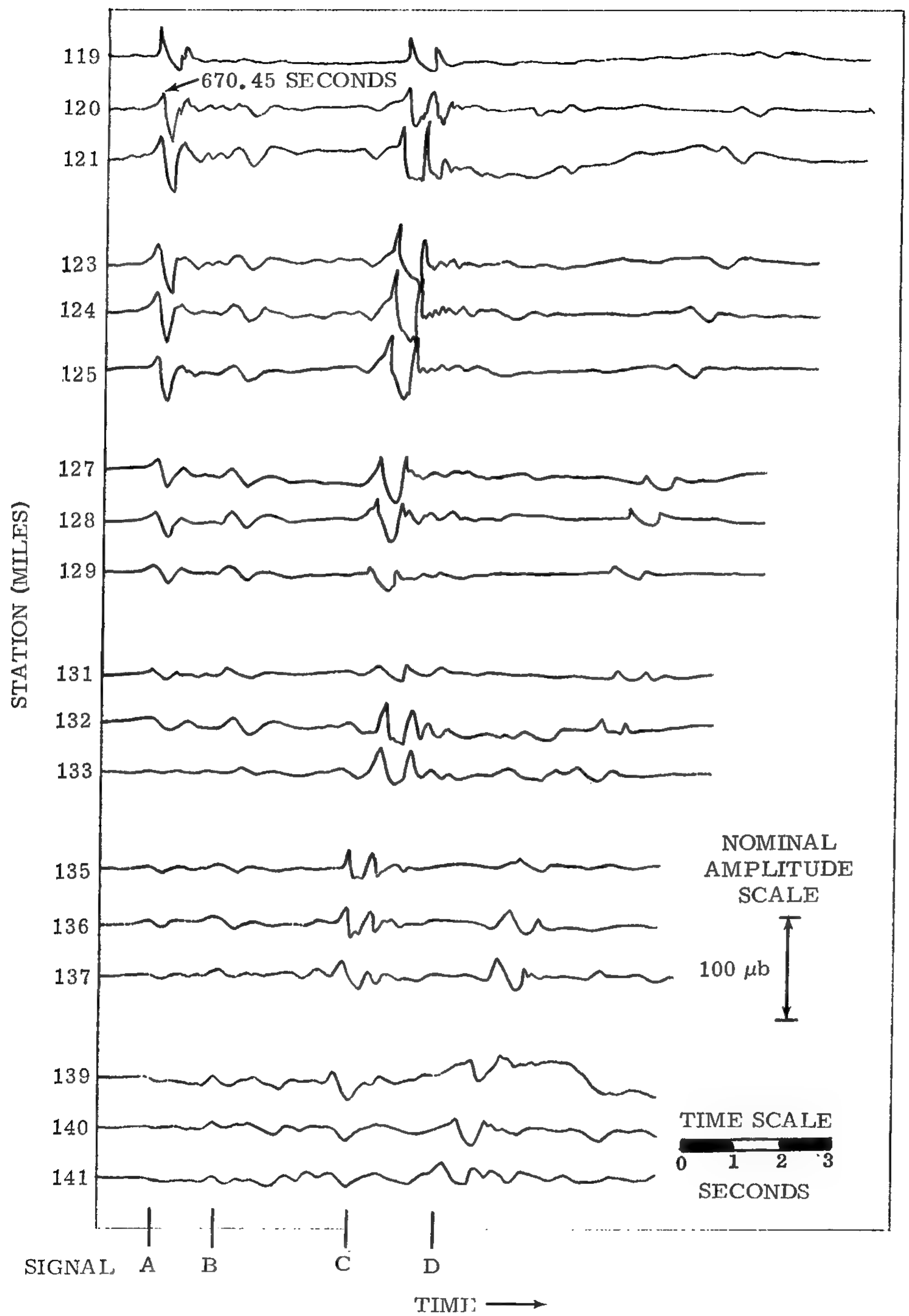

Figure 5. Microbarograph Recordings of First Calibration Shot, 1730 Z August 9, 1968

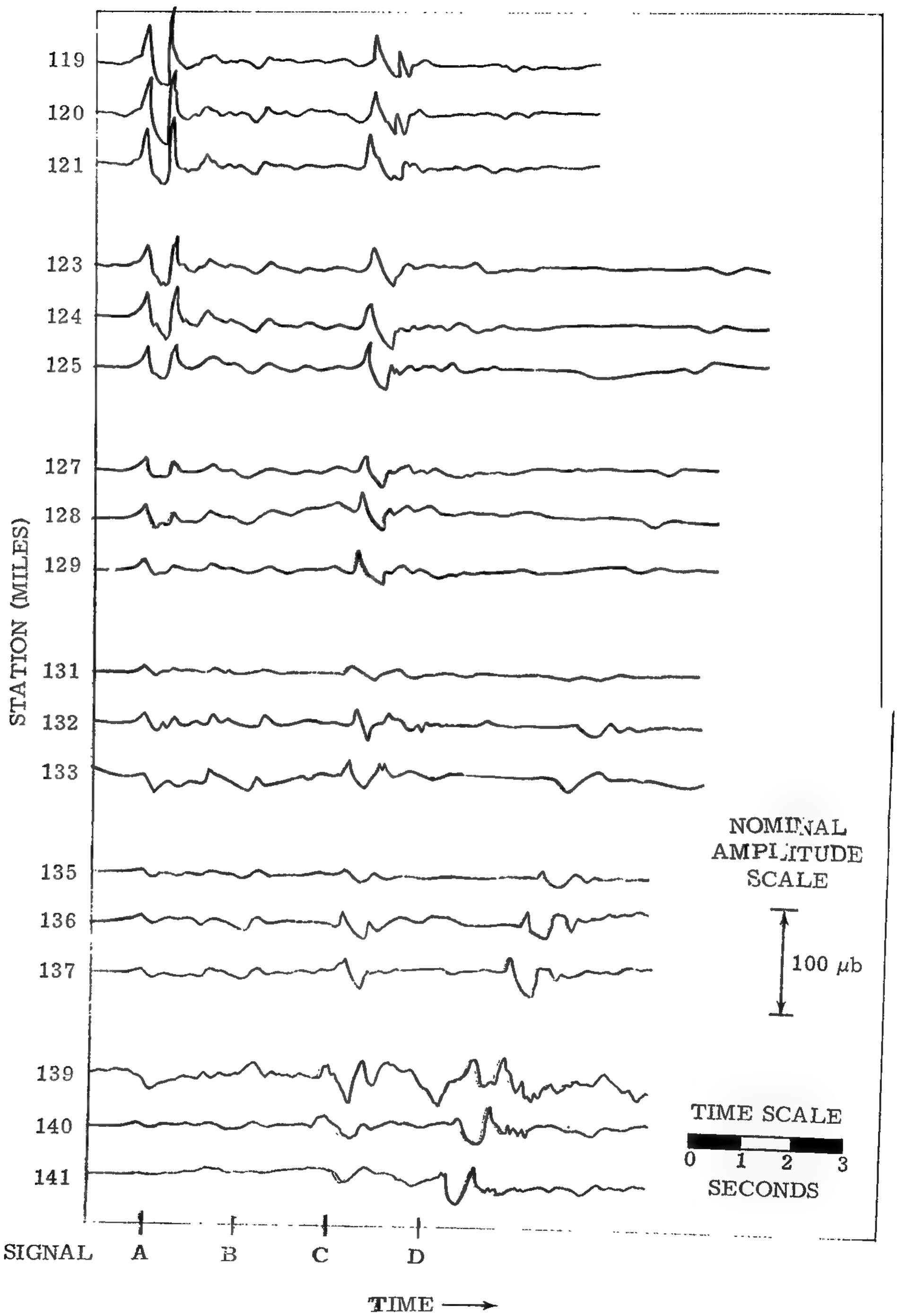

Figure 6. Microbarograph Recordings of Second Calibration Shot, 1745 Z August 9, 1968

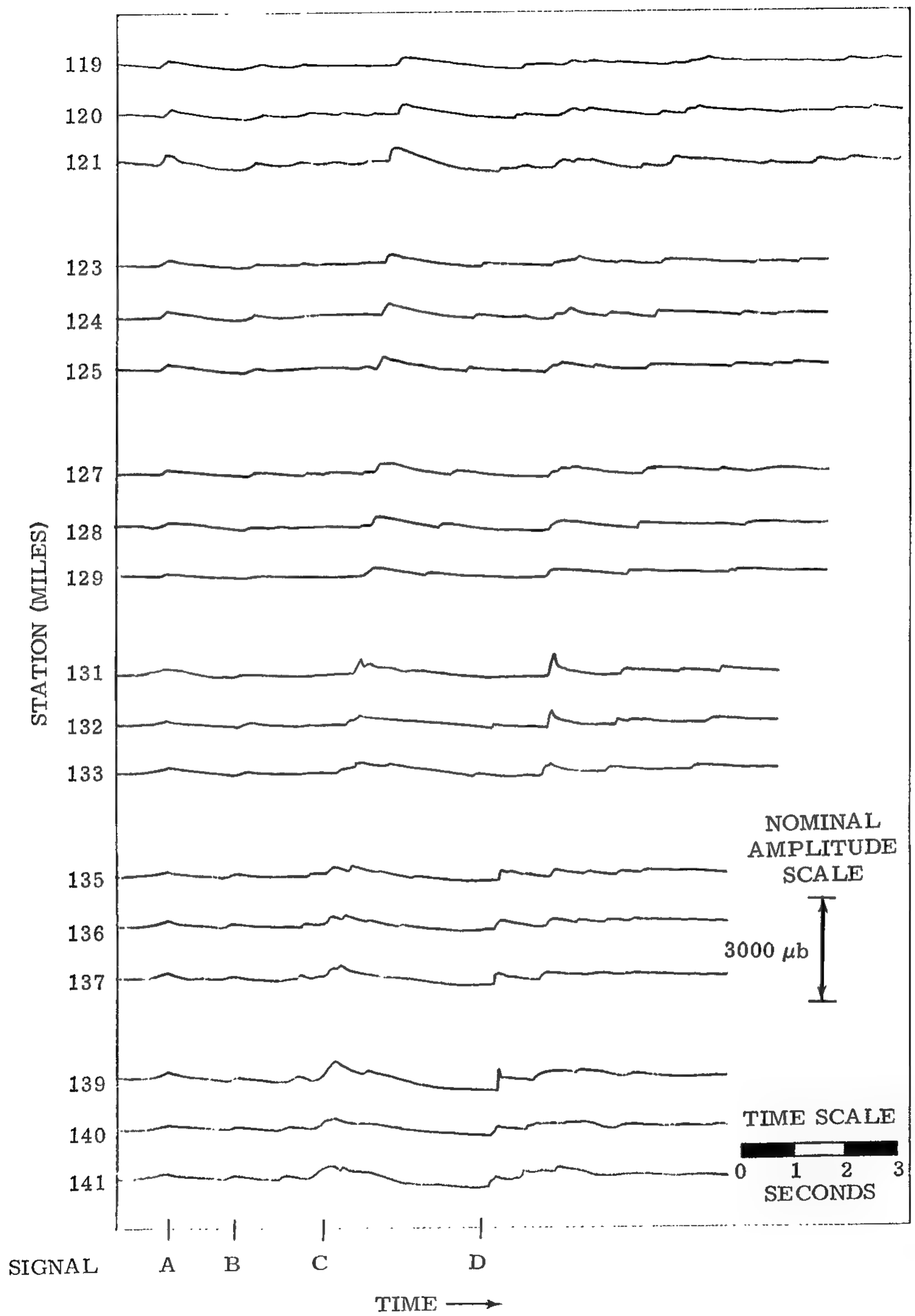

Figure 7. Microbarograph Recordings of PRAIRIE FLAT, 1800 Z August 9, 1968

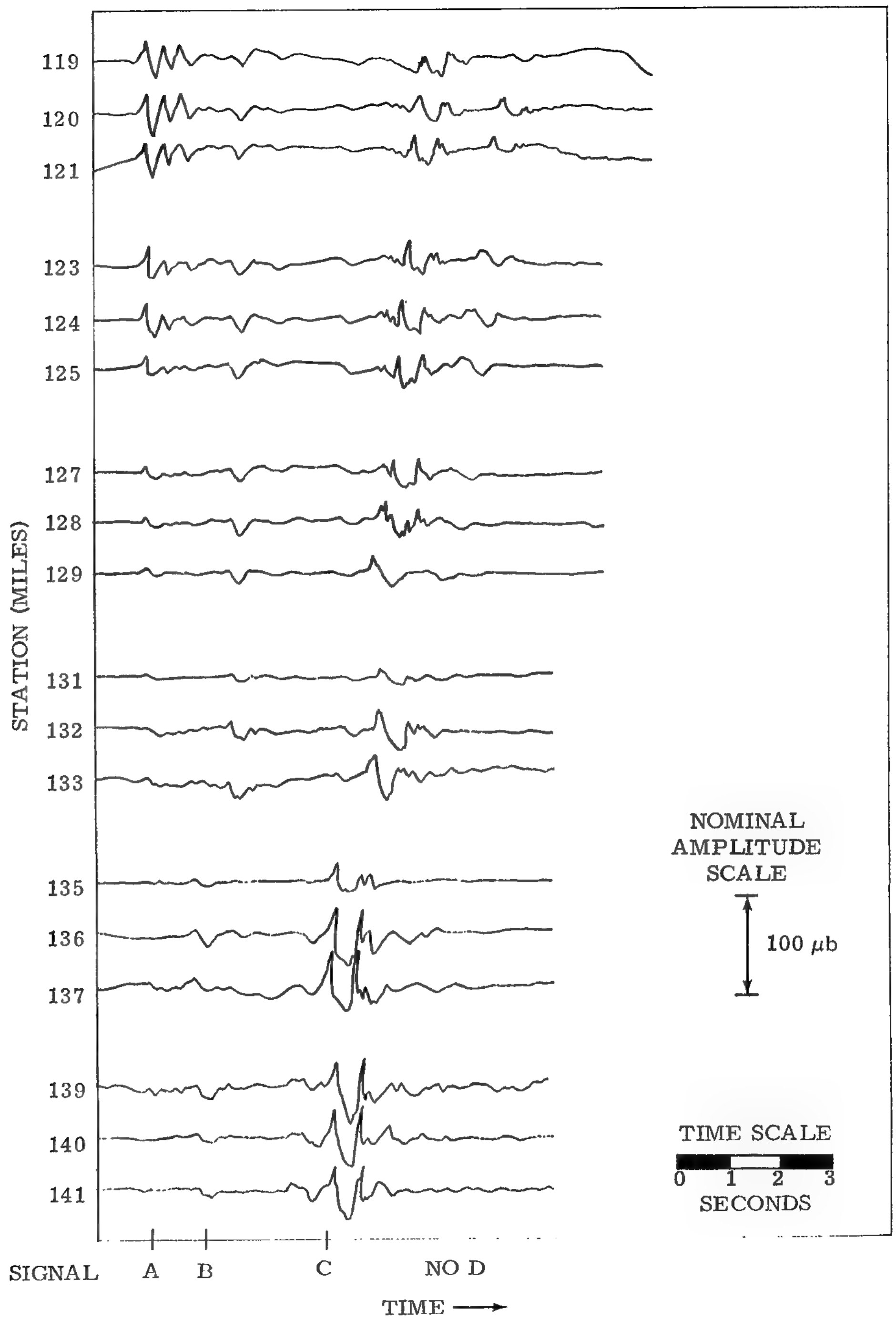

Figure 8. Microbarograph Recordings of Third Calibration Shot, 1815 Z August 9, 1968

TABLE II

CAL-1 Shot at Z -30 Minutes

Station	Signal A	Signal B	Signal C	Signal D	Remarks
	Amplitude (microbars)				
119	88	14	64	10	
120	68	18	59	14	
121	56	22	55	18	C' = 57
123	67	18	85	12	
124	52	18	81	16	
125	49	17	86	14	
127	33	20	54	18	
128	30	18	47	19	
129	27	22	35	17	
131	19	18	36	18	C' = 37
132	15	18	43	16	
133	--	--	34	17	Recording trouble
135	9	13	38	19	
136	8	14	29	27	
137	6	9	30	32	
139	7	9	25	20	D' = 23
140	8	6	16	29	
141	5	8	16	24	

TABLE III

CAL-2 Shot at Z -15 Minutes

Station	Signal A	Signal B	Signal C	Signal D	Remarks
	Amplitude (microbars)				
119	70	11	44		A' = 102
120	72	17	42		A' = 82
121	61	12	43		A' = 73
123	46	13	42	6	A' = 54
124	41	11	37	6	A' = 46
125	31	9	44	7	A' = 33
127	25	11	39	8	
128	24	13	36	7	
129	23	9	45	6	
131	16	10	28	9	
132	14	12	30	12	
133	16	19	26	13	D' = 18
135	12	14	27	28	
136	10	12	31	32	
137	10	11	36	44	
139	6	18	47	34	C' = 54, D' = 36
140	5	8	26	30	D' = 42
141	3	5	18	40	C' = 21, D' = 44

TABLE IV

PRAIRIE FLAT Shot at Zero Time

Station	Signal A	Signal B*	Signal C	Signal D	Remarks
	Amplitude (microbars)				
119	301		434	176	
120	318		464	191	
121	310		499	201	
123	253		429	285	
124	256		438	262	
125	232		448	265	
127	201		460	305	
128	199		470	302	
129	208		530	278	
131	184		487	367	D-spike 511
132	201		452	345	D-spike 515
133	210		443	355	
135	215		523	308	
136	220		570	294	
137	205		634	332	
139	196		697	328	D-spike 483
140	149		739	373	
141	145		685	319	

*B-Signal recording too small amplitude for confident comparison with CAL-shots.

TABLE V

CAL-3 Shot at Z +15 Minutes

Station	Signal A	Signal B	Signal C	Signal D*	Remarks
	Amplitude (microbars)				
119	44	13	26		C' = 30
120	41	14	26		
121	35	16	30		
123	30	13	35		
124	29	15	29		
125	21	16	32		
127	14	17	29		
128	9	16	34		
129	8	16	34		
131	8	15	33		
132	7	15	34		
133	7	13	42		
135	5	12	70		
136	3	15	83		
137	6	12	48		
139	4	11	52		C' = 55
140	2	12	82		C' = 86
141	2	10	58		C' = 59

*No "D" signal detected from this shot.

Distant Measurements

Records from the square array of four sensors at Pullman showed the PRAIRIE FLAT waves quite clearly. They are reproduced in Figure 9, and three significant signal times, A, B, and C, were established to aid in identification of the much weaker waves from calibration shots. This was not particularly successful since only the A-wave from the CAL-2 shot could be identified in the ambient noise, as shown in Figure 10. According to the provided recorder sensitivities, peak amplitudes for the A-waves were 12 to 18 μb from PRAIRIE FLAT. Amplitudes of 0.5 to 1.2 μb were shown from CAL-2. By comparison with MB array amplitudes at shorter range and slightly different bearing, these amplitudes are approximately an order of magnitude or factor of 10 lower than expected. There is some doubt and confusion about the correct sensitivity for these recordings which needs clarification. Group velocity for the PRAIRIE FLAT signals A, B, and C were 1051, 1000, and 915 fps, respectively.

Analyses

Ray Calculations

Ray path calculations were made using the weather data in Table I for directions toward the MB line at 270 degrees, and toward Pullman, Washington, at 227 degrees. Ray patterns for a 270-degree bearing (Figure 11) show sound ducting between about 140- and 180-kft altitudes, causing a ground-level sound ring at distances from 750 to 925 kft (142-172 miles) and just beyond the MB line. Were this exactly correct, the MB line would have been in a zone of silence and no blasts would have been recorded. Patterns toward a 227-degree bearing (Figure 12) show a narrow sound ring between 870 and 900 kft distance and a broad sound ring extending from 915 kft to nearly 1300 kft. This pattern is assumed to reflect from the ground and repeat its ray paths to longer ranges. At Pullman range, 2110 kft, this calculation shows that they should get the wave reflected near 1055 kft but three cycles of the calculated ring with a minimum range at 870 kft would strike well beyond the sensor array.

Calculated average wave arrival velocities are shown in Figure 13. These velocities are distances divided by arrival times, sometimes called group velocities. Calculated recorded amplitudes for calibration shot signals are graphed in dashed lines versus distances in Figure 14. Since the calculated sound ring landed beyond the station line it appeared pointless to try to directly compare recorded results with these calculations. Where no waves were predicted, the MB traces showed that several wave packets actually struck. The atmosphere apparently had several significant layerings which were not shown by the rocket wind report. These errors can be attributed either to observing error, over-smoothing, or to the measurement having been made 300 miles north of the actual wave paths.

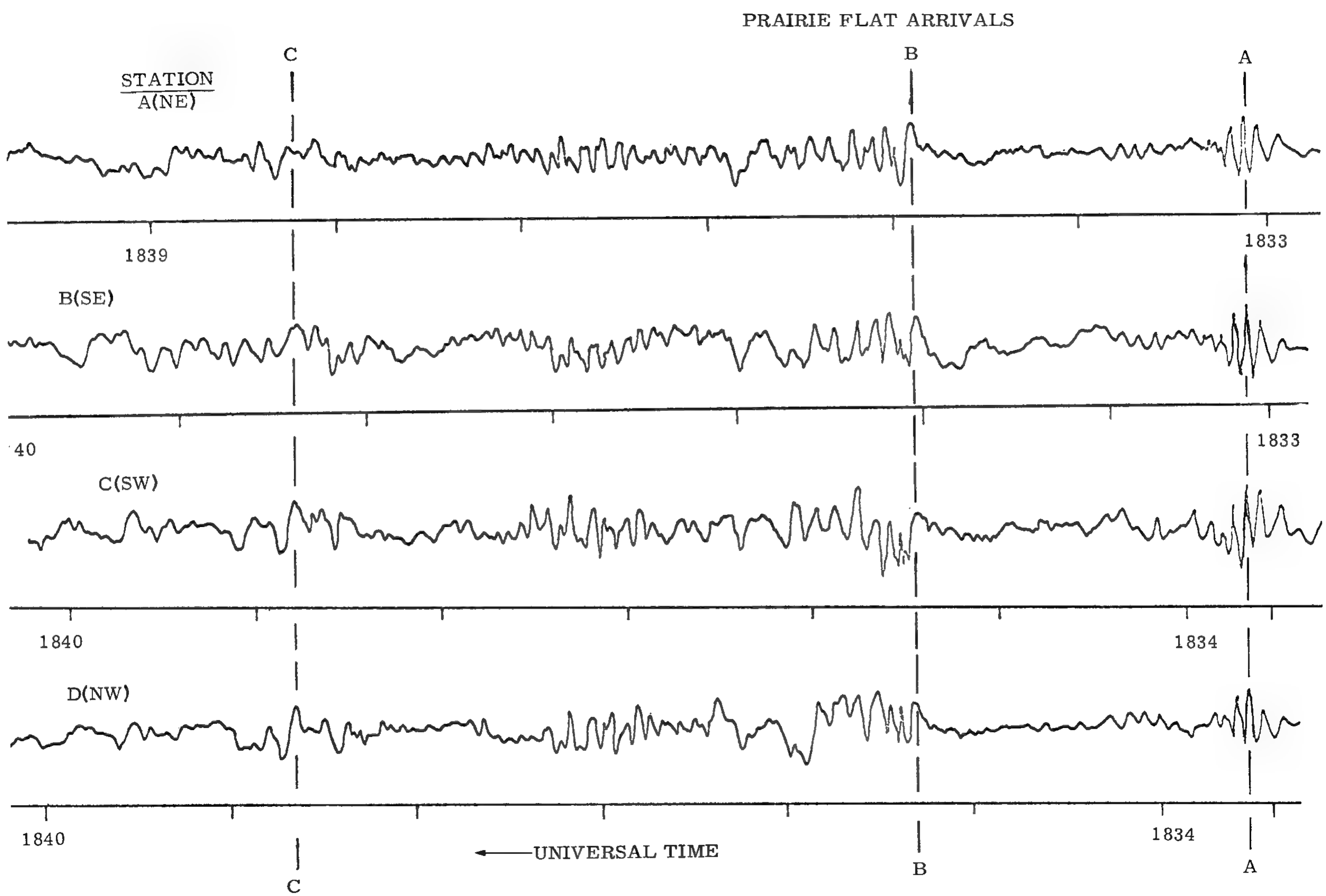

Figure 9. Acoustic Signals from PRAIRIE FLAT at Pullman, Washington

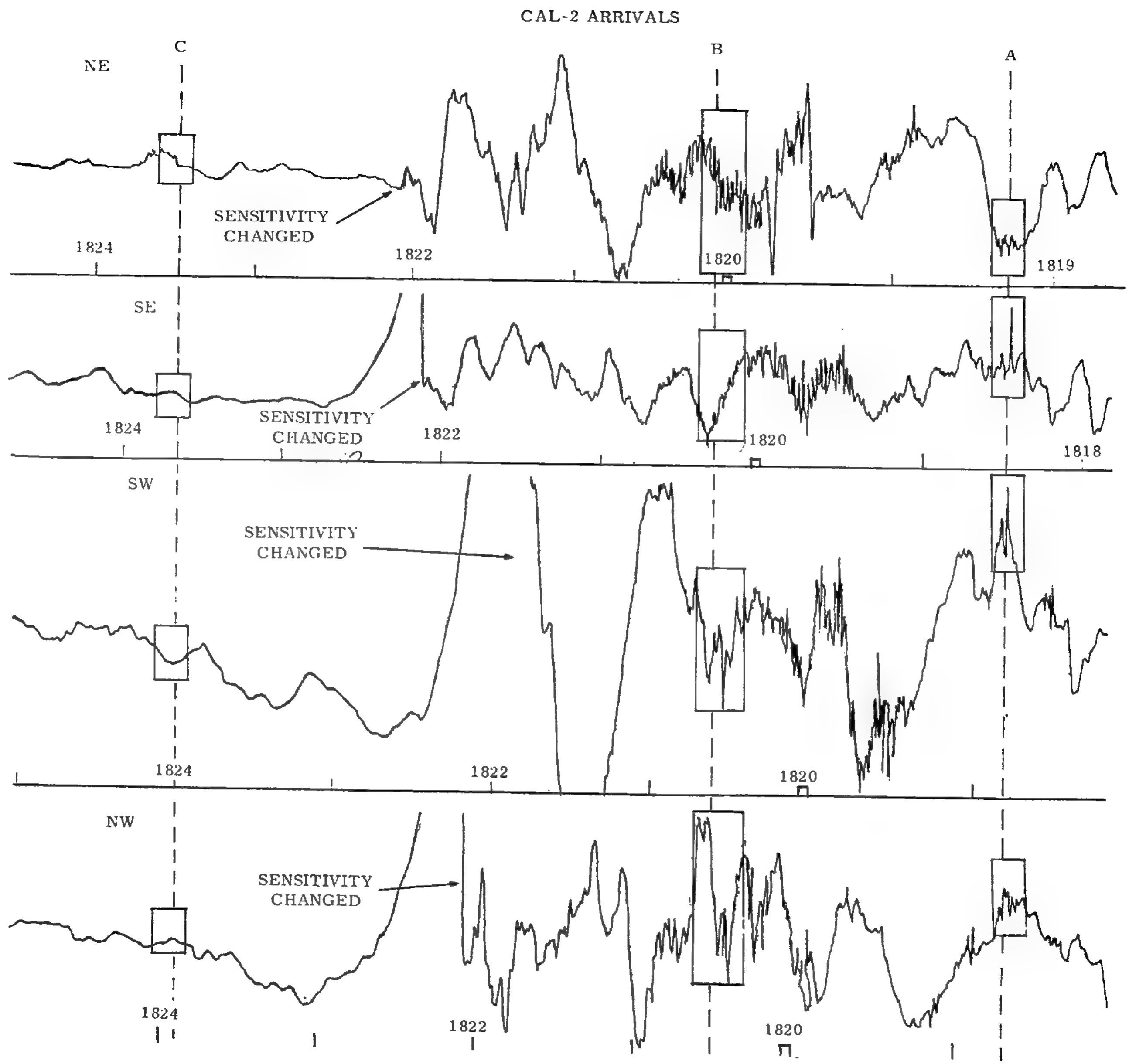

Figure 10. Pullman, Washington, Recordings at Expected Arrival Times for CAL-2 Shot Signals

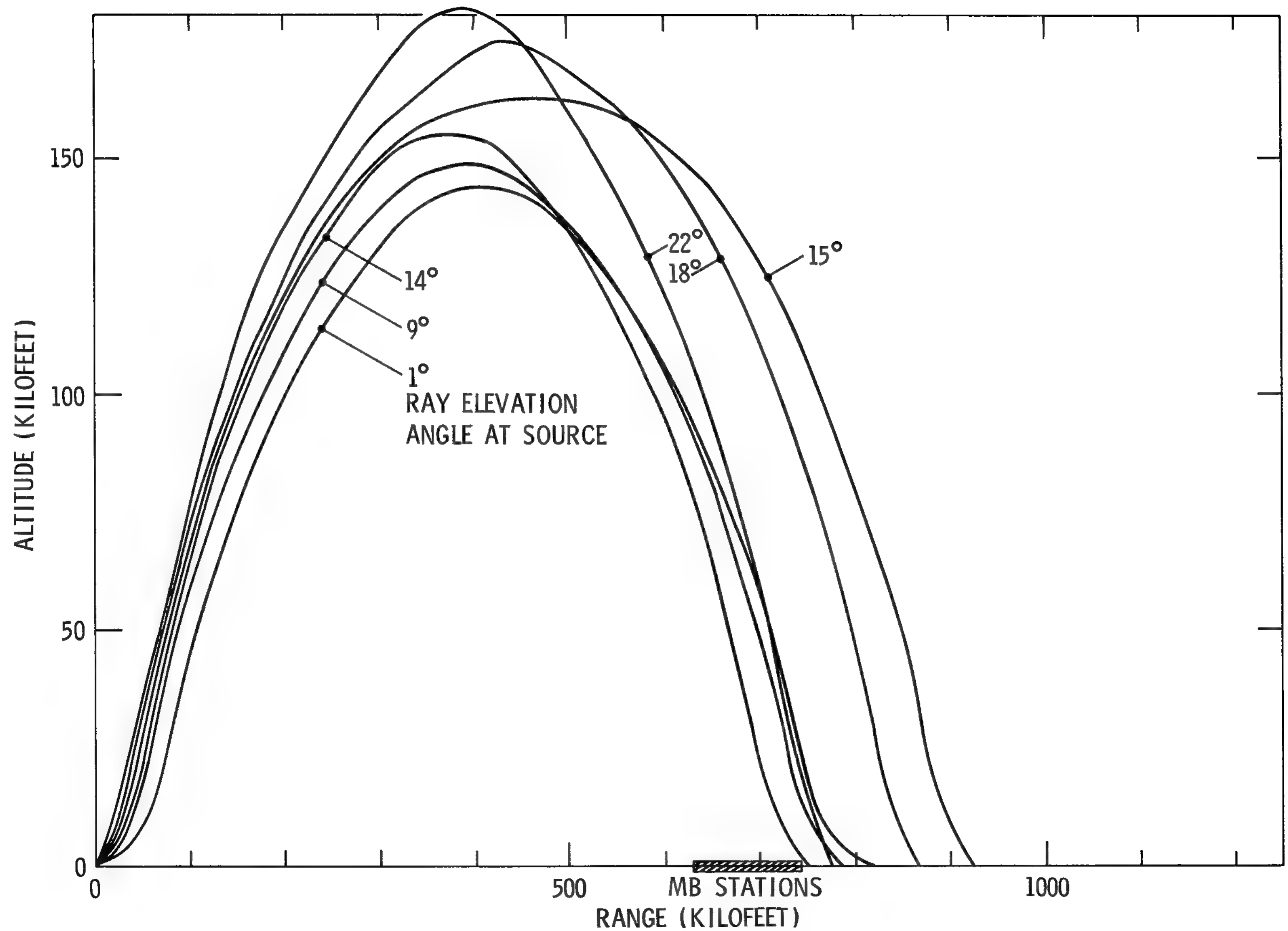

Figure 11. Calculated Ray Paths Toward Microbarograph Time at a 270-Degree Bearing

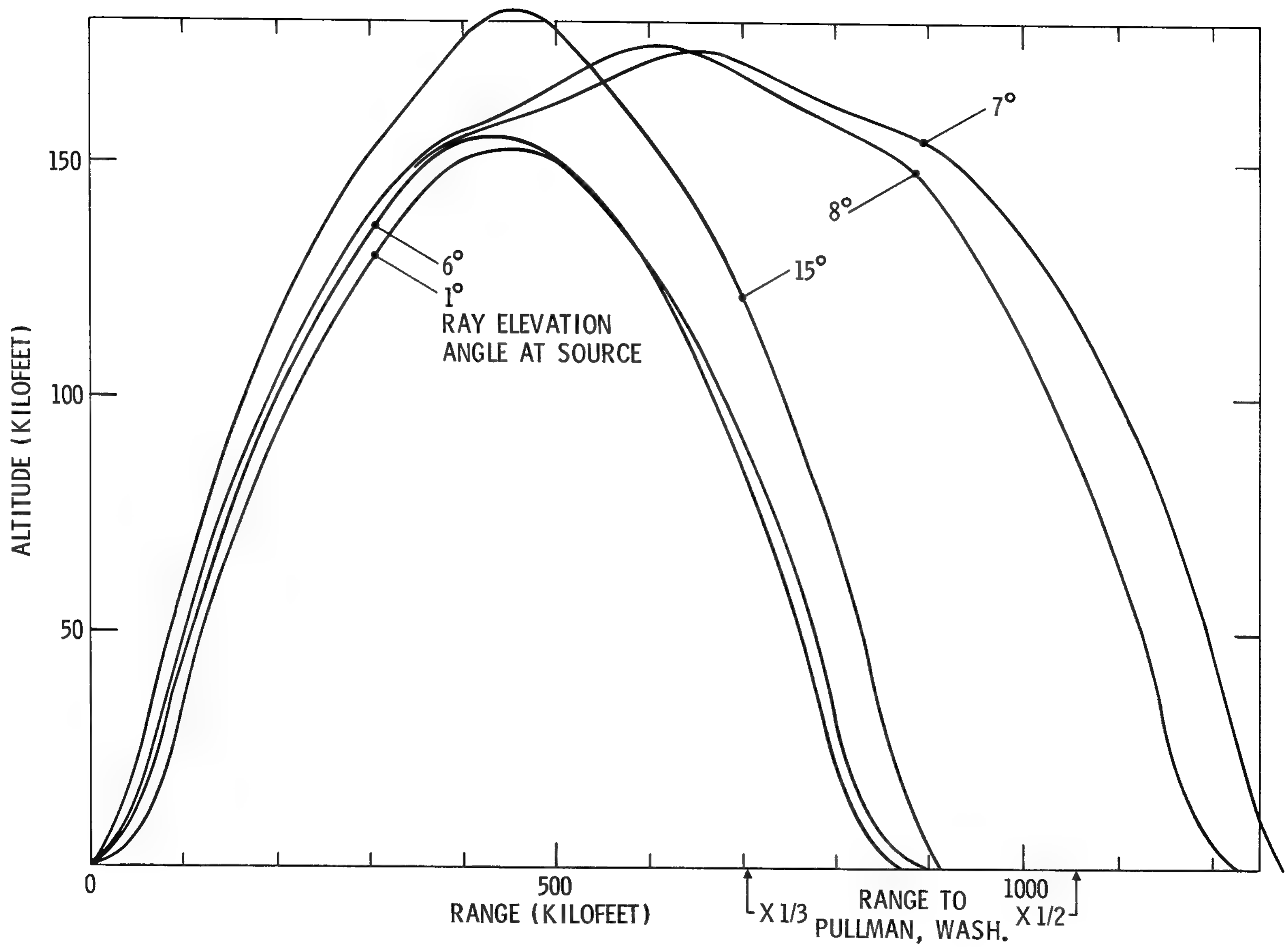

Figure 12. Calculated Ray Paths Toward Pullman, Washington, at a 227-Degree Bearing

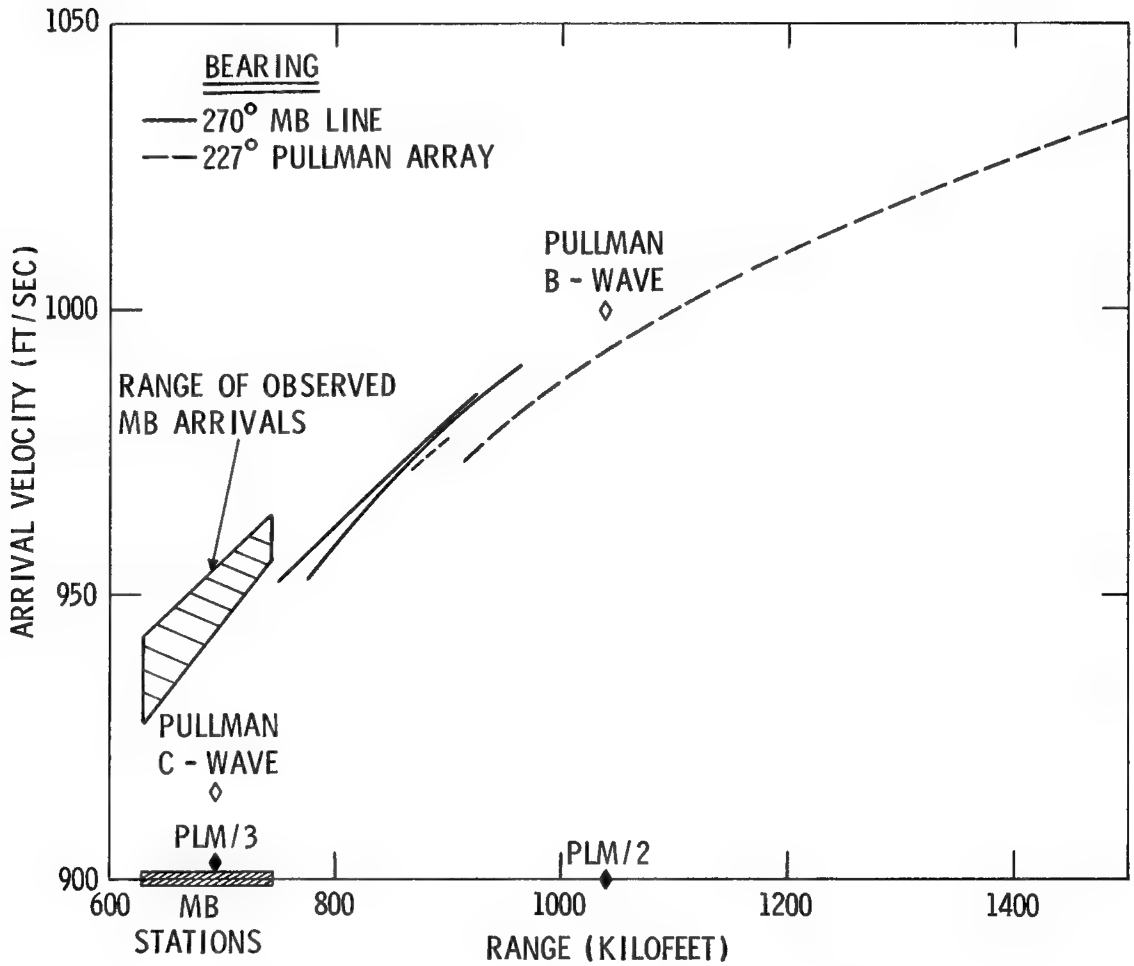

Figure 13. Calculated and Observed Ray Arrival Velocities

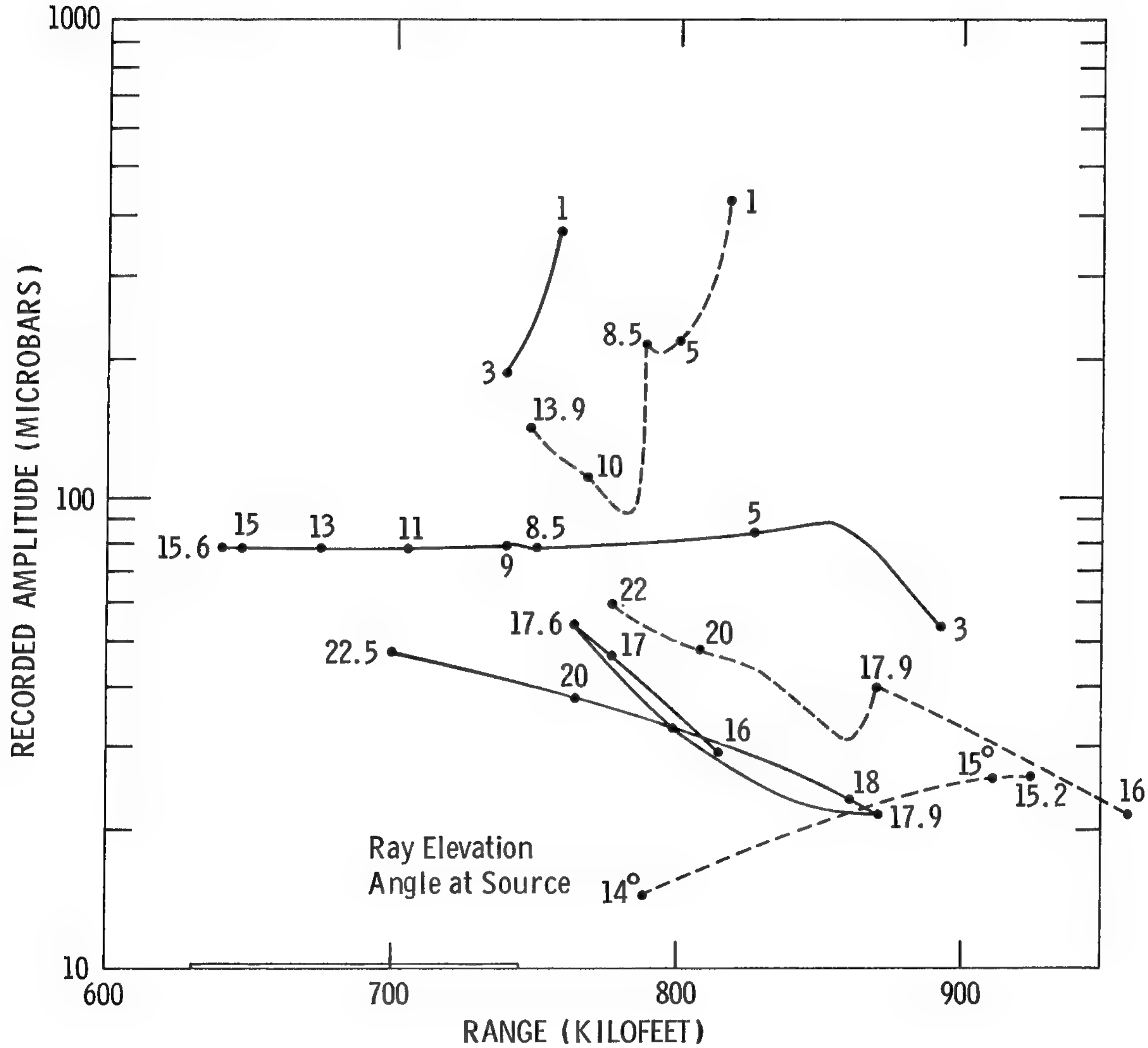

Figure 14. Calibration Shot Amplitudes, Calculated from Ray Path Patterns

In the era before rocket soundings, acoustic propagations were used to indirectly determine upper atmospheric structure. Early analyses by Crary[15] and Johnson and Hale[16] provided ranges of solutions to quite complicated calculations. These were much simplified by Reed[17] with a quasi-empirical description suited to analysis of large quantities of data obtained from nuclear test explosions. This simplified relation showed that a recorded wave ray had been reflected at altitude, z, where

$$z = R\,(0.865 - 0.789\,\overline{V}/V_p)$$

where R is horizontal range, and $\overline{V}$ is wave arrival or group velocity. Phase velocity, V_p, sometimes called characteristic velocity, is the apparent horizontal velocity of the wave passing along the ground between two sensors. It is also the local propagation velocity at the altitude where reflection took place. Pairs of sensors were placed a mile apart on a radial from an explosion, at known long distances. Recordings of several waves, each with different arrival time, $\overline{V}$, and V_p, thus allowed calculation for points in the directed (z, V) structure. Curves were obtained in several directions from the explosion, and the set was resolved to give temperature, wind speed, and wind direction versus altitude for the reflecting layer or layers.

This method was resuscitated to give points of (z, V) from observed PRAIRIE FLAT MB signals for comparison with the sounding data shown earlier in Figure 4. These points showed that some higher velocities were needed in the region from 120 to 170 kft to explain the observations. Four wave groups observed on the first two calibration shots required four reflecting levels, so there must be more zig-zags in the (z, V) curve than the rocket sounding showed. It thus appeared that the soundings should be "adjusted" to help explain the wave recordings.

A new atmosphere was fabricated by alternately adding and subtracting 20 ft/sec of zonal wind at levels intermediate to the Arcas report levels, as shown by the jagged curve in Figure 4. Ray calculations for this atmosphere did not completely explain the multiplicity of recorded waves, but, as shown by the solid-line curves in Figure 15, it gives two waves in parts of the MB line plus a near-grazing third wave at the far extreme. Further manipulation could no doubt generate four arrivals, but an adjustment with time would also be needed to cut out the fourth group arrival, as was observed from the third calibration shot. For the present, the qualitative explanation must suffice that predicted or calculated details in the pattern would not be verified.

Arrival velocities from the revised calculations in Figure 15 were compared to observed arrivals, dashed curves, from three waves, A, C, and D. The general discrepancy of about 10 fps may be attributed to errors in assumed mean wind speed or to location inaccuracy. Stations were not surveyed, nor were explosion locations precisely defined, and map measurements were used to estimate distances. A 1.5-mile correction would be needed and this is probably little more than the likely map-reading error. The total error probably stems from the combined sources and is not particularly significant, being only 1.2 percent in travel time.

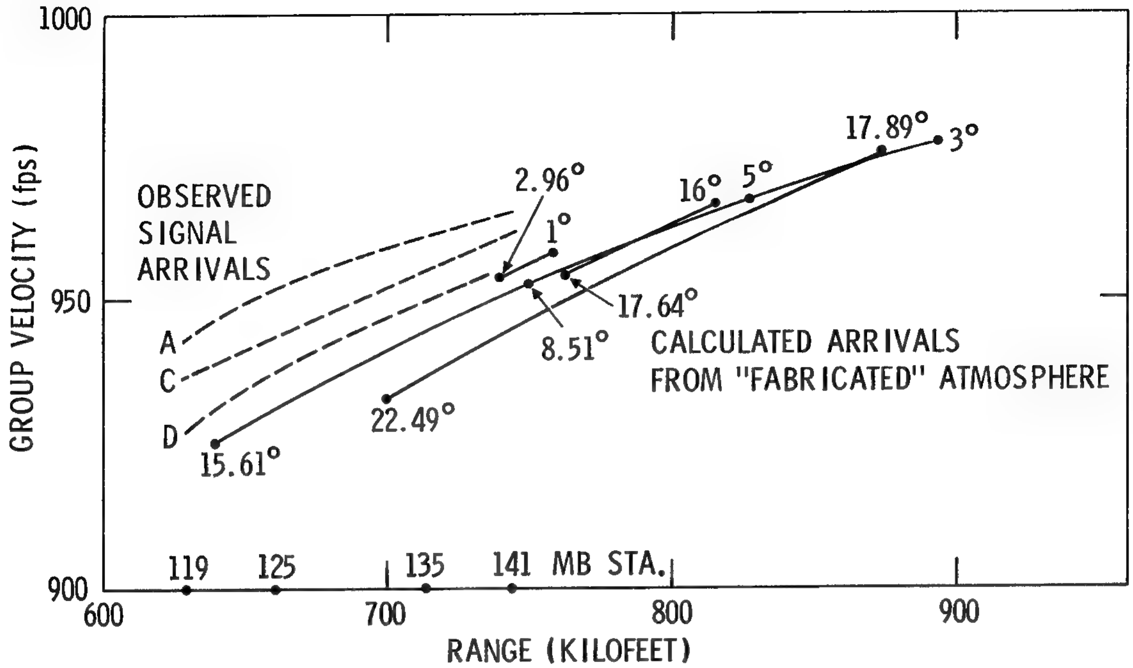

Figure 15. Arrival Velocities Calculated from "Fabricated" Sounding Data

One further question raised by these data is that the earliest signal (A) traveled over the MB line at about 1104-fps phase velocity, and near the local sound speed, so it was very nearly grazing the surface. It, nevertheless, had some high recorded amplitudes at the nearest stations, and may not have been doubled by ground reflection. The difficulty, however, is that Suffield ambient velocity at ground level from Table I weather data was 1126 fps, so that there would have been no rays emitted with lower characteristic or phase velocities. Where did the A-wave come from? One hypothesis is that its source was in diffraction or scattering from near the 1-degree ray path in Figure 11 at about 100-kft altitude, and that considerably more wave energy was scattered into the "silent" zone than was expected.

The three signals at Pullman, Washington appear to have reasonable arrival times according to Figure 13. The A-signal probably propagated without reflecting from around 180 kft MSL, the B-signal was once reflected, and the C-signal was twice reflected by the ground.

Observed Amplitude Patterns

Amplitudes in Tables II through V resulted after several corrections were made besides the standard MB-set calibration corrections. Raw calibrated data for some stations showed systematic departures from smoothed amplitude versus distance plots on all calibration explosions and all wave groups which indicated calibration error. An averaged empirical correction was then derived for each MB set. This was not done for PRAIRIE FLAT because set recording ranges

were changed by switching to contain the larger signals and this empirical correction cannot be assumed to persist over switch-changed sensitivites.

Tabulated amplitudes for calibration shots have been plotted versus station number (distance in miles) in Figures 16, 17, and 18. Smoothed curves of amplitude versus distance have been drawn through them with dashed lines for the various wave groups. If it is assumed that instrument error had been removed, the residual variance around the smoothed curves represents local variations caused by small-scale atmospheric irregularities, i. e., turbulence. A similar presentation of PRAIRIE FLAT records is given in Figure 19.

Smoothed curves for each particular wave packet have been collected in Figures 20, 21, 22, and 23, for waves A, B, C, and D, respectively. PRAIRIE FLAT waves have been plotted with amplitudes reduced in proportion to apparent yield to the 0.4 power, the assumed scaling rule. In Figure 20 the shifts needed to change to other scaling power laws are also shown. Curves of standard explosion recorded amplitude versus distance are also given for reference along with some curves for focus factor F = 2.0.

Review of these figures indicates that local deviations from the smoothed curves may be statistically distributed. It is not clear, however, that the humps and bumps which drift through Figures 16 through 23, with influence over 10- to 20-mile regions, are amenable to simple statistical treatment. This result differs from results of recording in jet-stream caustics[2] where bumps in the amplitude-distance curves seldom spanned more than a few miles and few sensors. This newly observed continuity with distance does not allow the conclusion that extremely large amplitudes might have occurred in the unobserved spaces between sensors, at least for ozonosphere ducted waves.

It does appear that there is considerable independence between signal groups, as was visibly evident from record reproductions in Figures 5 through 8. There is no strong indication that the caustic was missed by this array, as the first ray calculation showed. The occasional humps on the C-wave and D-wave curves near 140 miles may be what was looked for to define the caustic. With some alternative smoothing adjustments, particularly to the D-wave in Figure 17, and the C-waves in Figures 18 and 19, it could still be concluded that the caustic was missed and fell outside the array. These data are too rough to confidently select between these conclusions. The best conclusion seems to be that the calculated caustic was considerably mixed up by small-scale atmospheric structure, which did not persist over 15-minute periods, and that the multiplicity of real resulting "caustics" were the bumps where amplitudes were doubled over 6- and 8-mile-wide bands.

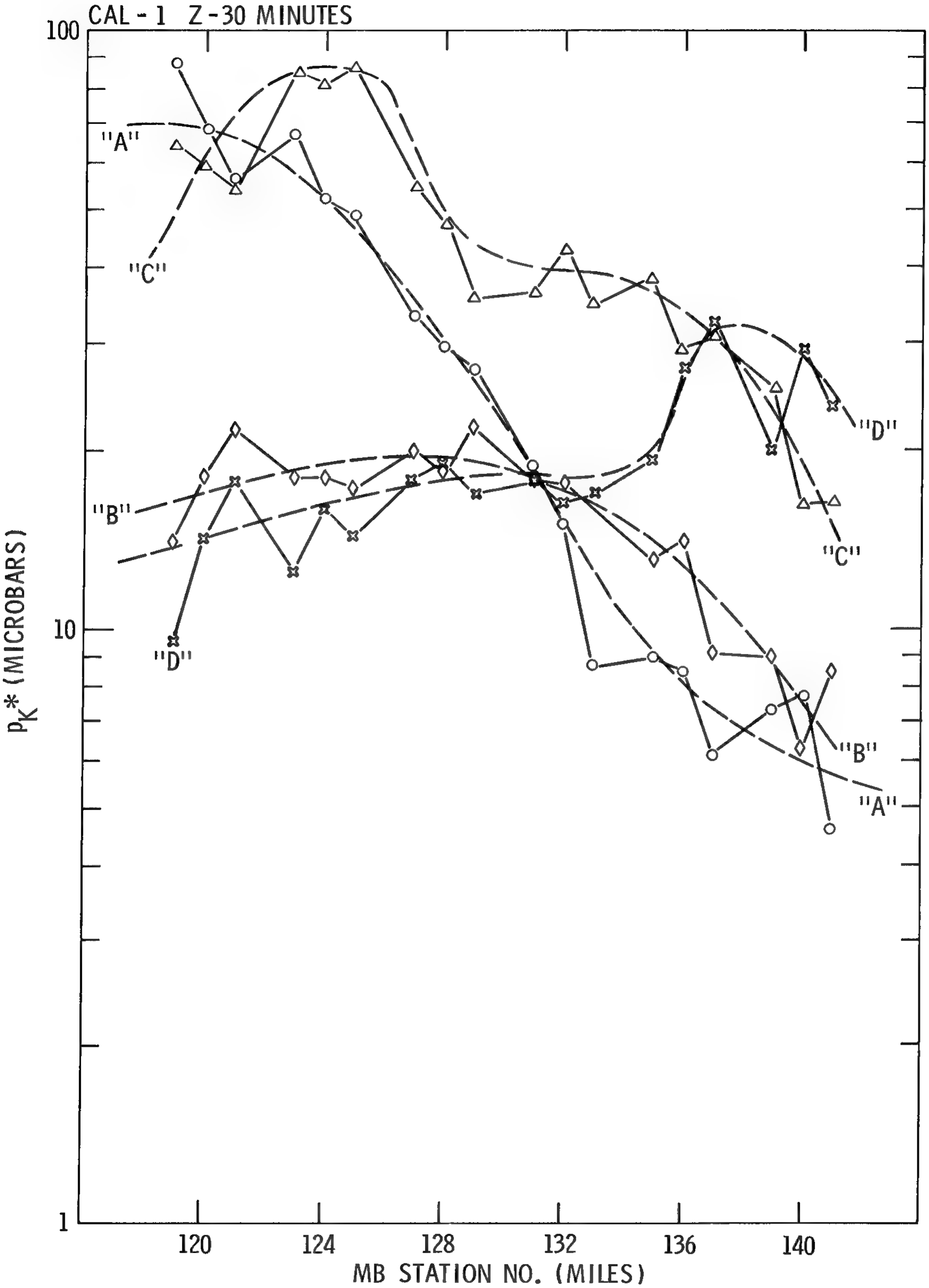

Figure 16. Recorded Amplitudes, CAL-1 Shot, Versus Distance

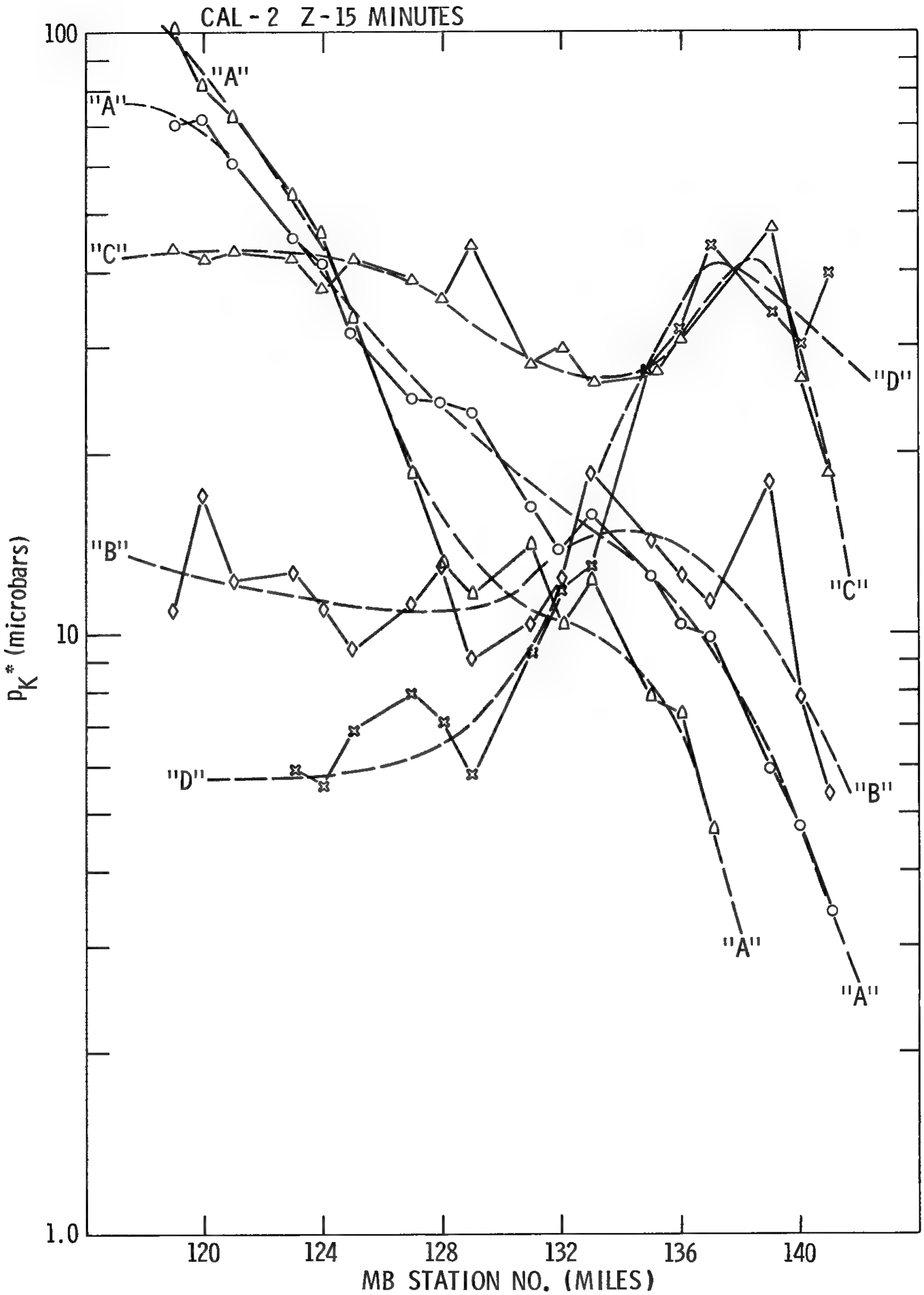

Figure 17. Recorded Amplitudes, CAL-2 Shot, Versus Distance

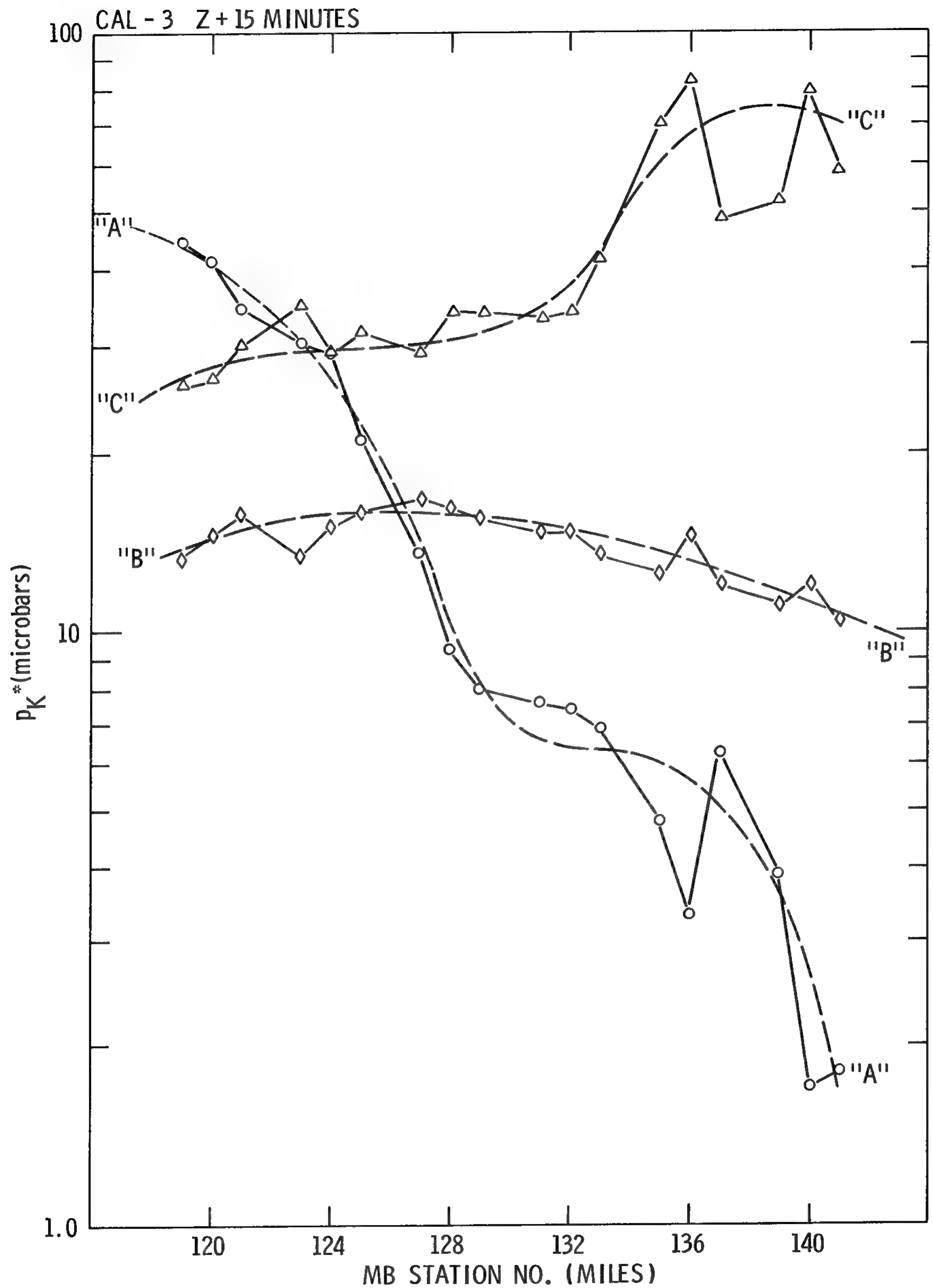

Figure 18. Recorded Amplitudes, CAL-3 Shot, Versus Distance

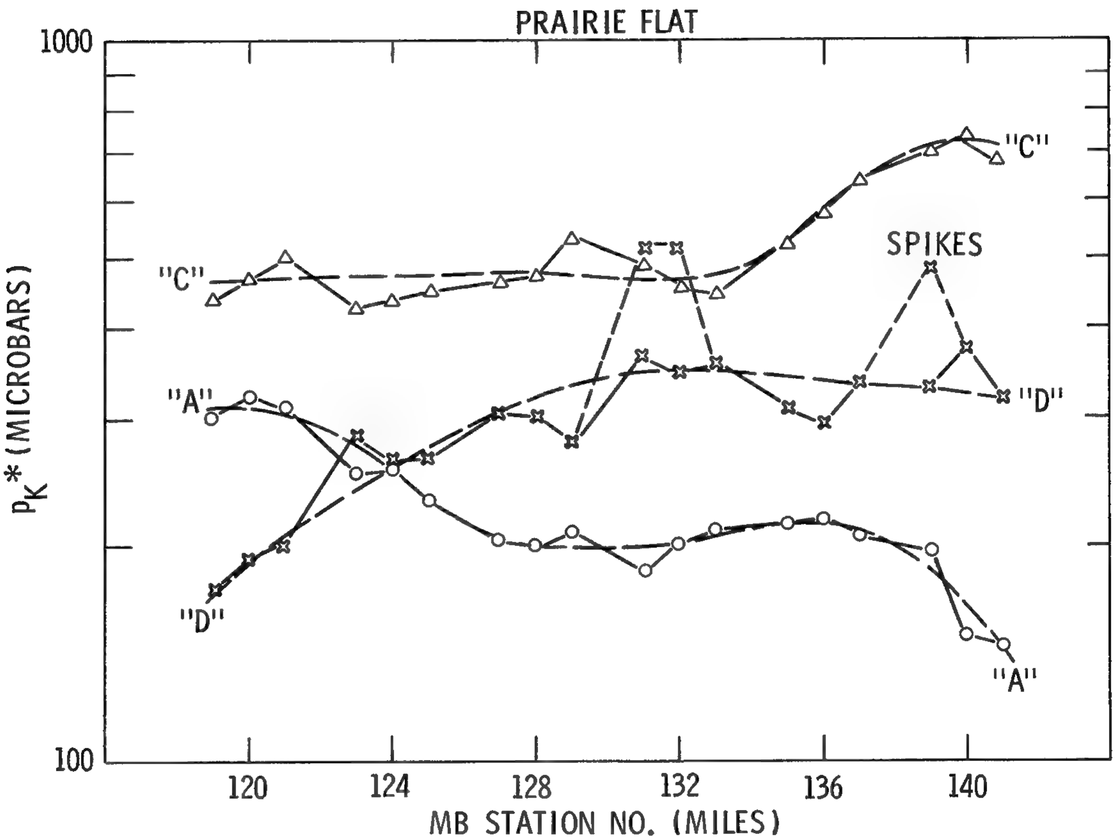

Figure 19. Recorded Amplitudes, PRAIRIE FLAT, Versus Distance

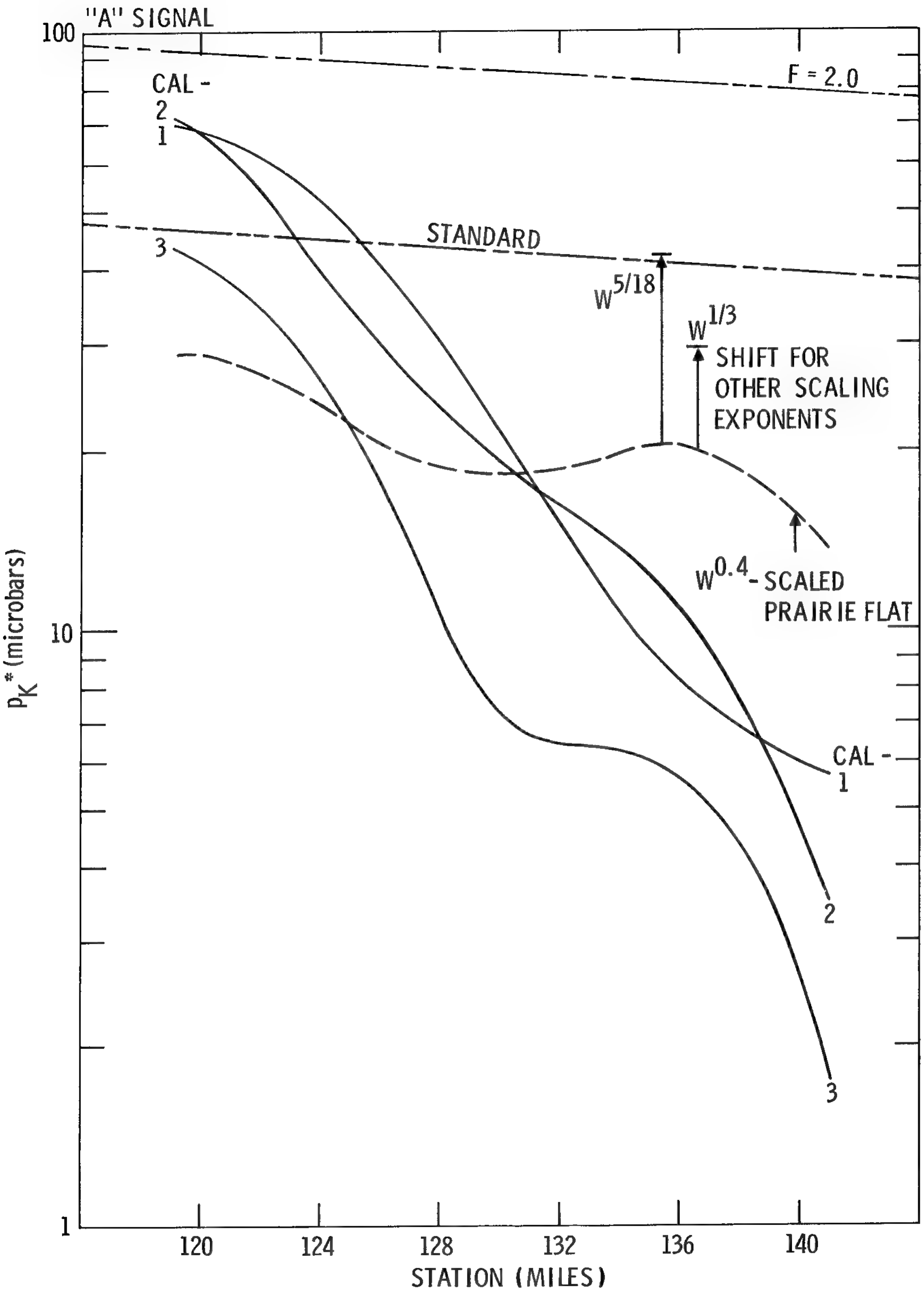

Figure 20. Smoothed Curves for Wave Packet A

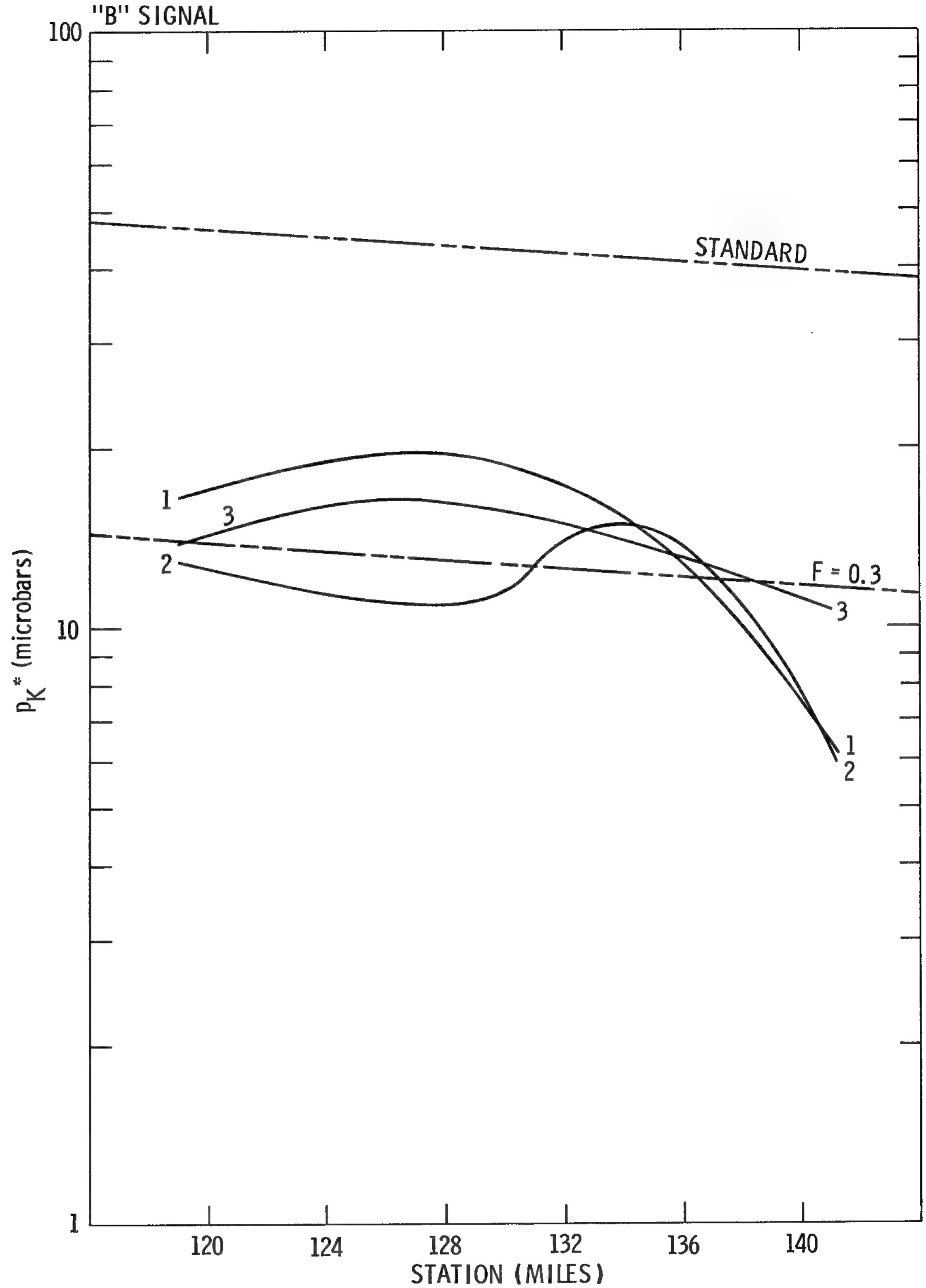

Figure 21. Smoothed Curves for Wave Packet B

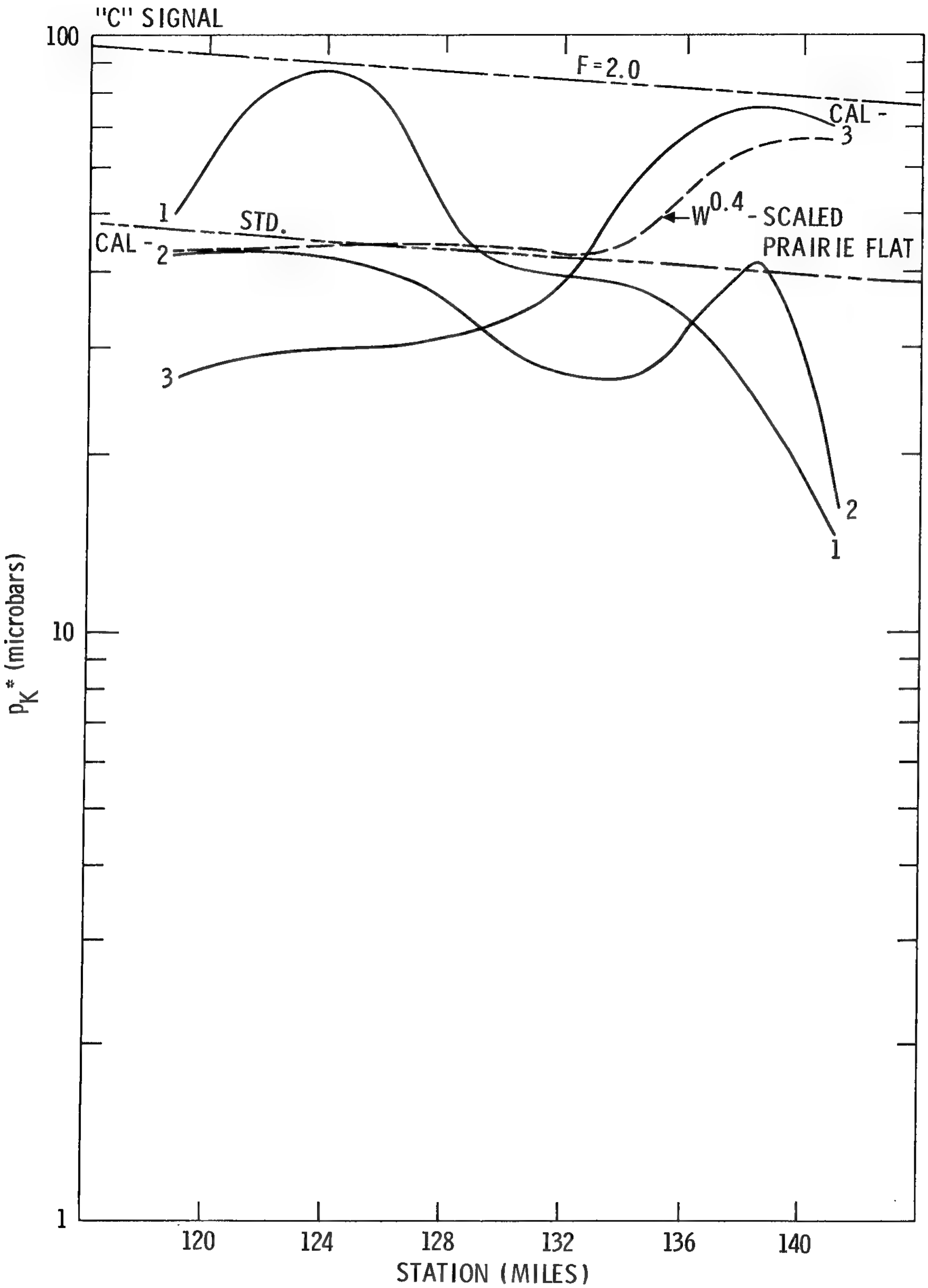

Figure 22. Smoothed Curves for Wave Packet C

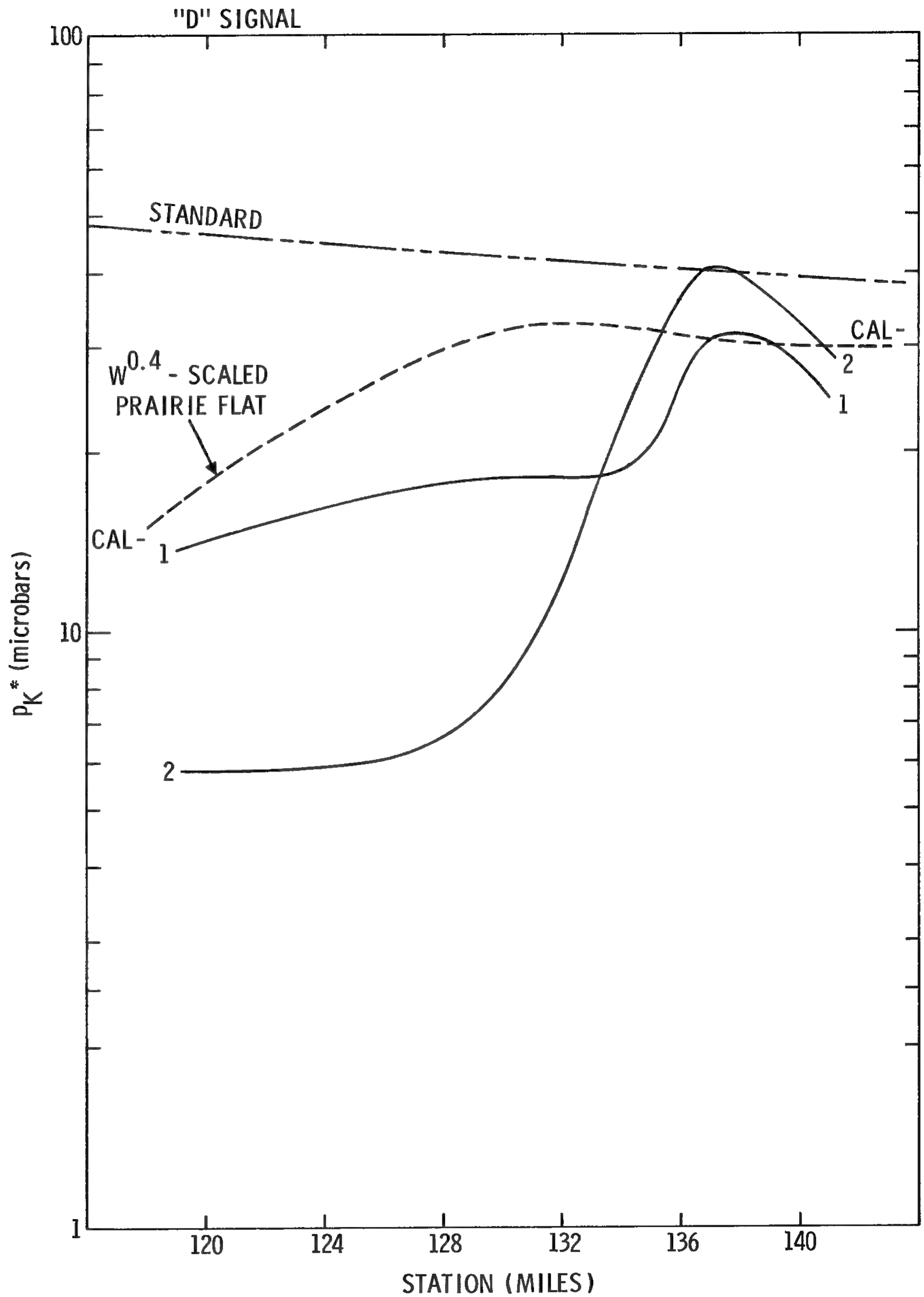

Figure 23. Smoothed Curves for Wave Packet D

In hopes of separating variances between instrument error, turbulent variability, and wave group differences, the smoothed curves of Figures 20, 21, 22, and 23 for the four signal groups A, B, C, and D were averaged; results are shown in Figure 24. It turned out that the factor of two group variability, that is the difference between smoothed curves for successive shots, was so great as to overwhelm other variances. There was also an appreciable error variance from "eyeball" smoothing, so that in some station ensembles the variance of both calibrated and corrected data were smaller than the "total" variance between the smoothed curves. It thus appears that instrument error and small-scale turbulent effects, though they appear to make ragged data curves, do not increase the net uncertainties by more than about 10 percent.

Among the smoothed curves, waves A, C, and D were maxima, each for at least some shots and stations. Wave B was included in the previous analysis because it was so consistently observed from the three calibration shots. Data from B-waves were not used in determining maximum amplitude probabilities, for it never showed the maximum amplitude.

There is no gross explanation for the double bump in the averages of Figure 24, and, with the possible exception of data at the far end of the MB line, the total of data can probably be assumed to represent a single statistical population, for statistical prediction. This assumption was made and waves A, C, and D were averaged for all stations and calibration shots (Wave D was not recorded from CAL-3). The geometric average amplitude for these three wave groups was 22.4 μb* and the geometric standard deviation was calculated to be a factor of 2.27. The total distribution for three waves from each shot was plotted in Figure 25 along with the computed log-normal curve. These data do not show a very good fit to the log-normal distribution. Of most importance is the downward curvature at larger amplitudes and low probabilities. This shows that there was some damper limiting the occurrence of very high amplitudes.

Responding structures would care only about maximum amplitudes and not whether it was a first, second, or third wave group arrival. Therefore, maxima for each station and shot were also analyzed, but these also did not give a log-normal distribution, as is clearly shown by the distribution curve in Figure 26. The limitation on maxima is again clearly indicated near 90 μb.

These are not exactly the same statistics as were reported for jet-stream caustics[2] where 15 shot events were analyzed. Here maxima are defined as, for a single station and shot, the largest amplitude of the three or four wave groups recorded. This is the same as the amplitude reported in jet-stream data where the multiplicity of wave cycle and groups was ignored and the maximum amplitude was reported from each recording. The P-F calibration shot distribution of maxima in Figure 26 is shown around the mean for 17 stations and 3 shots, and the scatter around the mean for a single shot would be slightly smaller, since the shot means range ±4 percent around the mean for three shots. The scatter factor of 1.43 should thus be slightly reduced for direct comparison with the jet-stream test value of 1.55. Comparison thus shows somewhat less variability through the array for ozonosphere duct waves than was observed in Nevada for jet-stream duct waves.

*Note that the increase from Figure 24 was caused by deleting weak B-waves from averages.

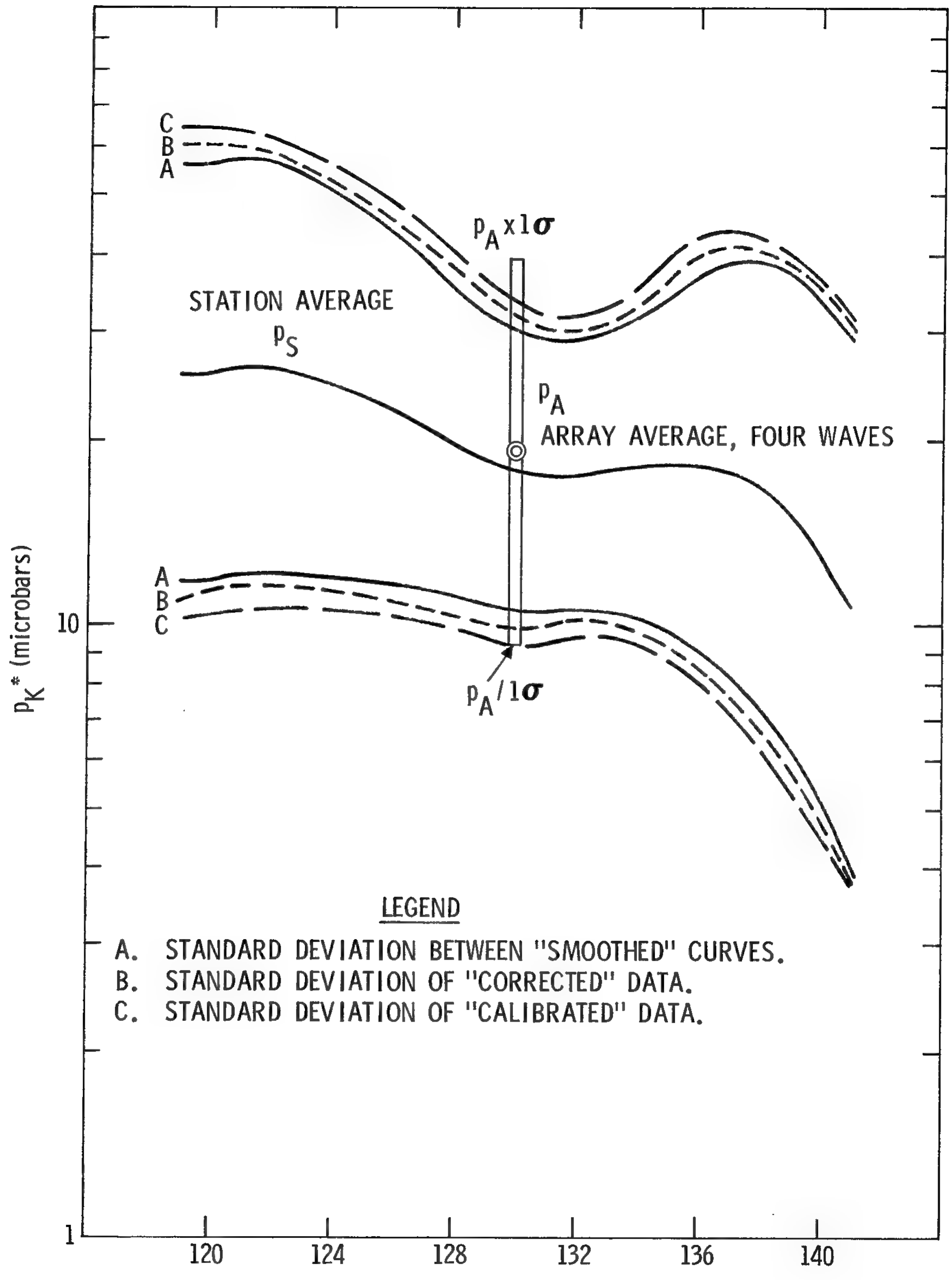

Figure 24. Station Geometric Averages and Deviations of Group Amplitudes, Waves A, B, C, and D

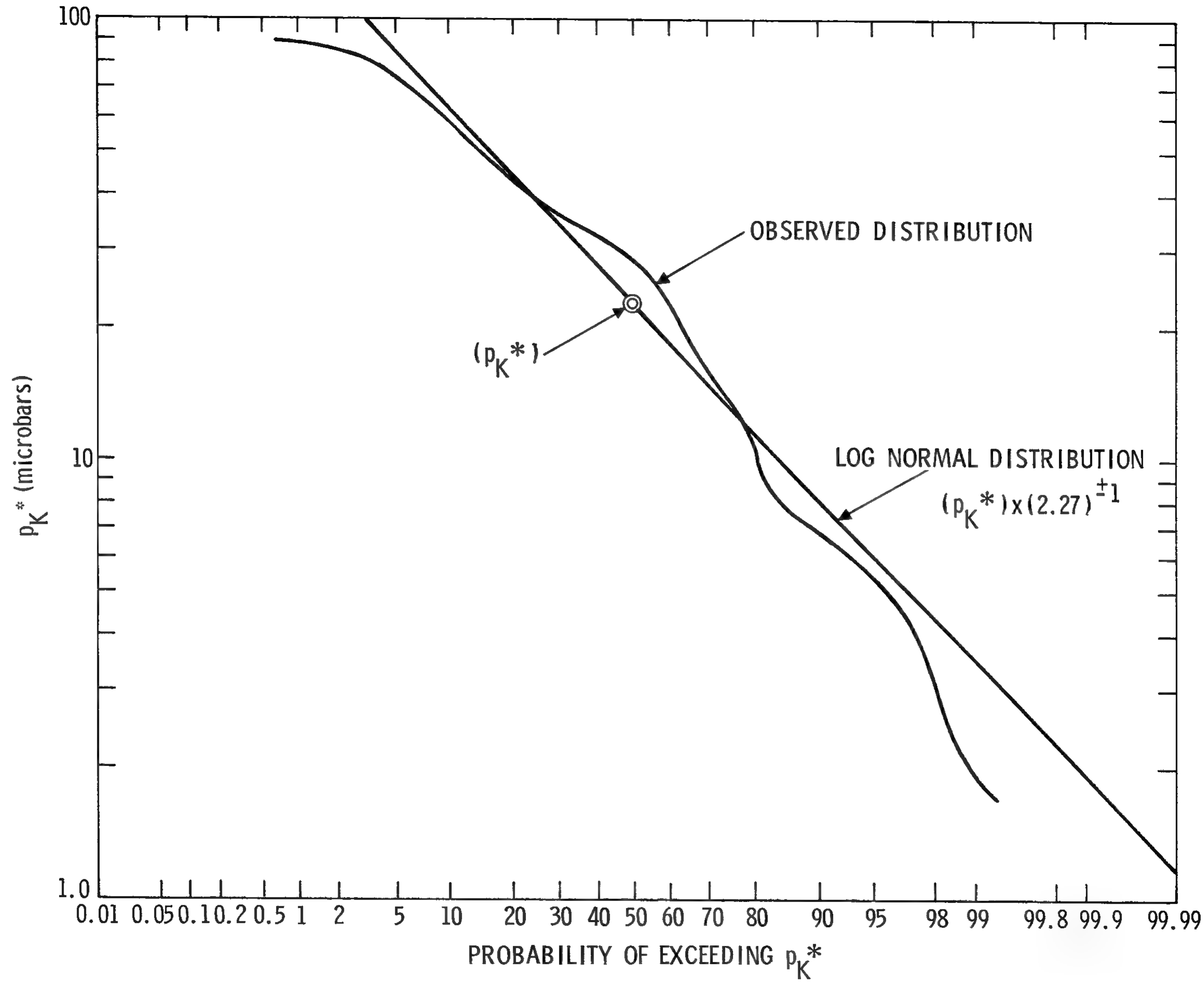

Figure 25. Distribution of Amplitudes of Major Calibration Shot Waves

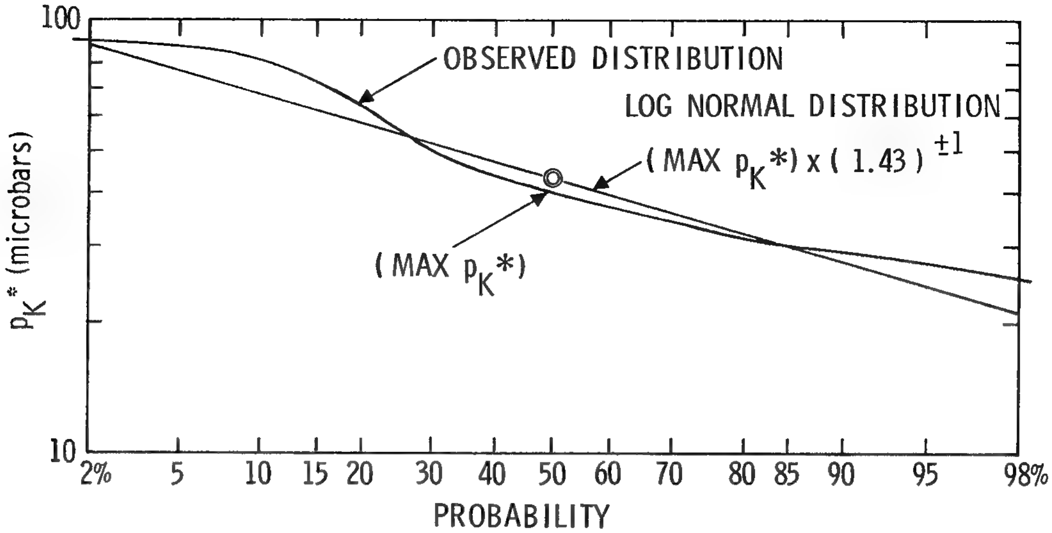

Figure 26. Distribution of Amplitude Maximum from Shots and Stations

Concern with the apparent restriction to extreme maxima is because damage estimation by Reed[17] shows that a concentration of costs would be incurred in statistical areas where about three times the mean maximum amplitudes occur. These areas are in the 10^{-3} probability region for being recorded by a single sensor under jet-stream ducting conditions. It is not clear from Figure 26 that three times the mean amplitudes would ever be found by extrapolation of the observed distribution, so that damage estimation may be considerably affected.

Since real concern is with larger yields where the amplitude distribution may be influenced by lower wave frequencies, further discussion of this calibration shot data will be dropped.

In the PRAIRIE FLAT event data, every maximum amplitude came in the C-signal group. In fact, every C-wave was stronger than any A or D wave recorded. For comparison with calibration shot statistics, however, distributions were calculated for the (A, C, D) set as shown in Figure 27, with both calculated arithmetic averages and logarithmic averages. For C-waves alone, $p_K^* = 523 \pm 96\ \mu b$ for the normal distribution, and $p_K^* = 523 \times (1.21)^{\pm 1}\ \mu b$ for the computed log-normal distribution. Scatter for this wave is appreciably smaller than the 1.43 scatter factor for maxima from calibration shots. The logarithmic variance has been reduced by a factor of 3.53, while the charge weight (note that actual weight is used and not blast-apparent yield) is increased by 400 so that wavelength is increased by $(400)^{1/3} = 7.37$. More comparative data for other yields are necessary to estimate a form for this relationship between yield or wavelength and effective scattering power of the atmospheric irregularities which appear to have caused these variations.

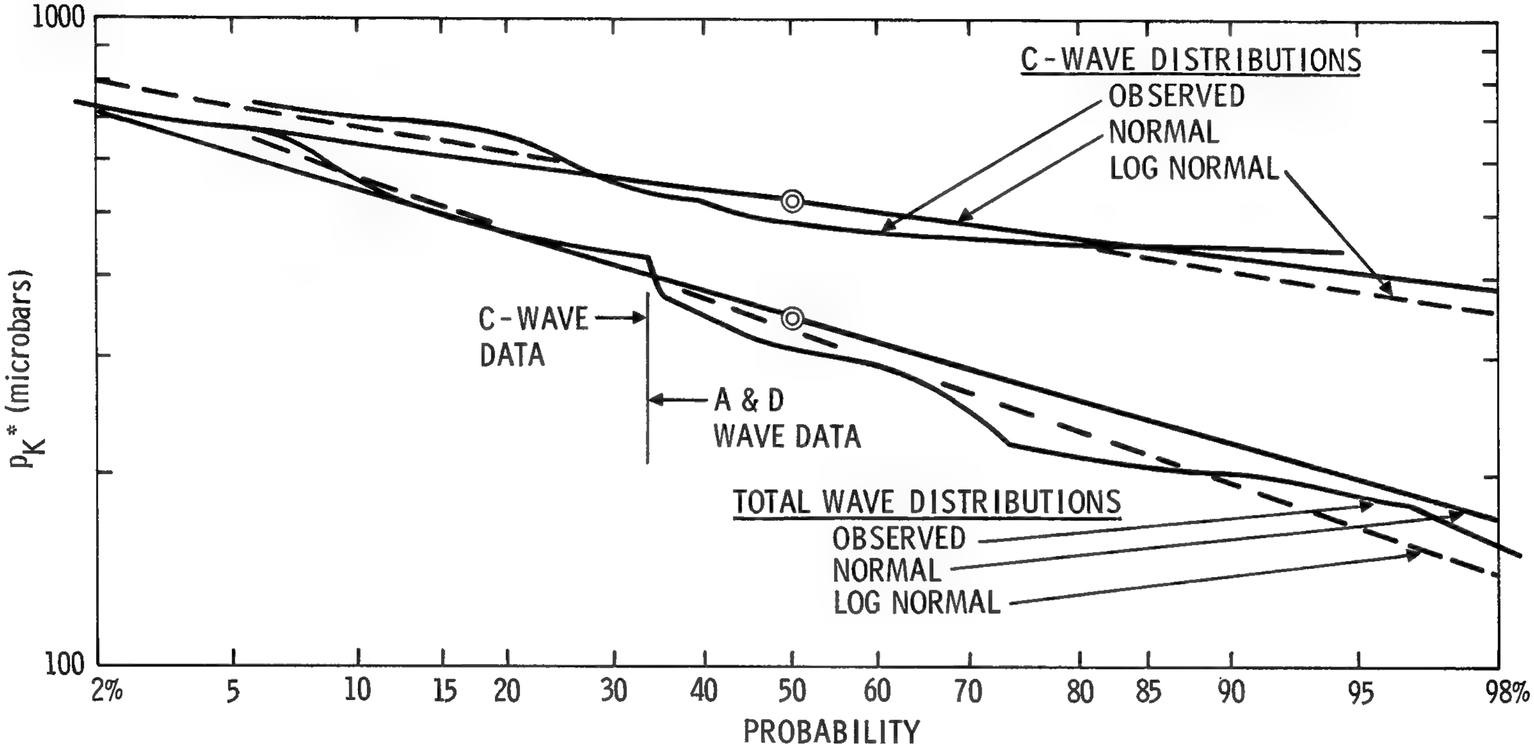

Figure 27. Distribution of PRAIRIE FLAT Amplitudes

In further comparison, averages by wave and shot were plotted in Figure 28, for calibration shots versus PRAIRIE FLAT. If $p_p/p_c = (W_p/W_c)^A$, where blast-apparent yields are used and (p, c) subscripts refer to PRAIRIE FLAT and calibration shots, the overall average A = 0.425 obtains. Various forms of scatter give specific comparison values of $\frac{1}{3} < A < \frac{1}{2}$. Considering this scatter, there is little significance to the observed variations from A = 0.40 which was obtained from Project BANSHEE.[17]

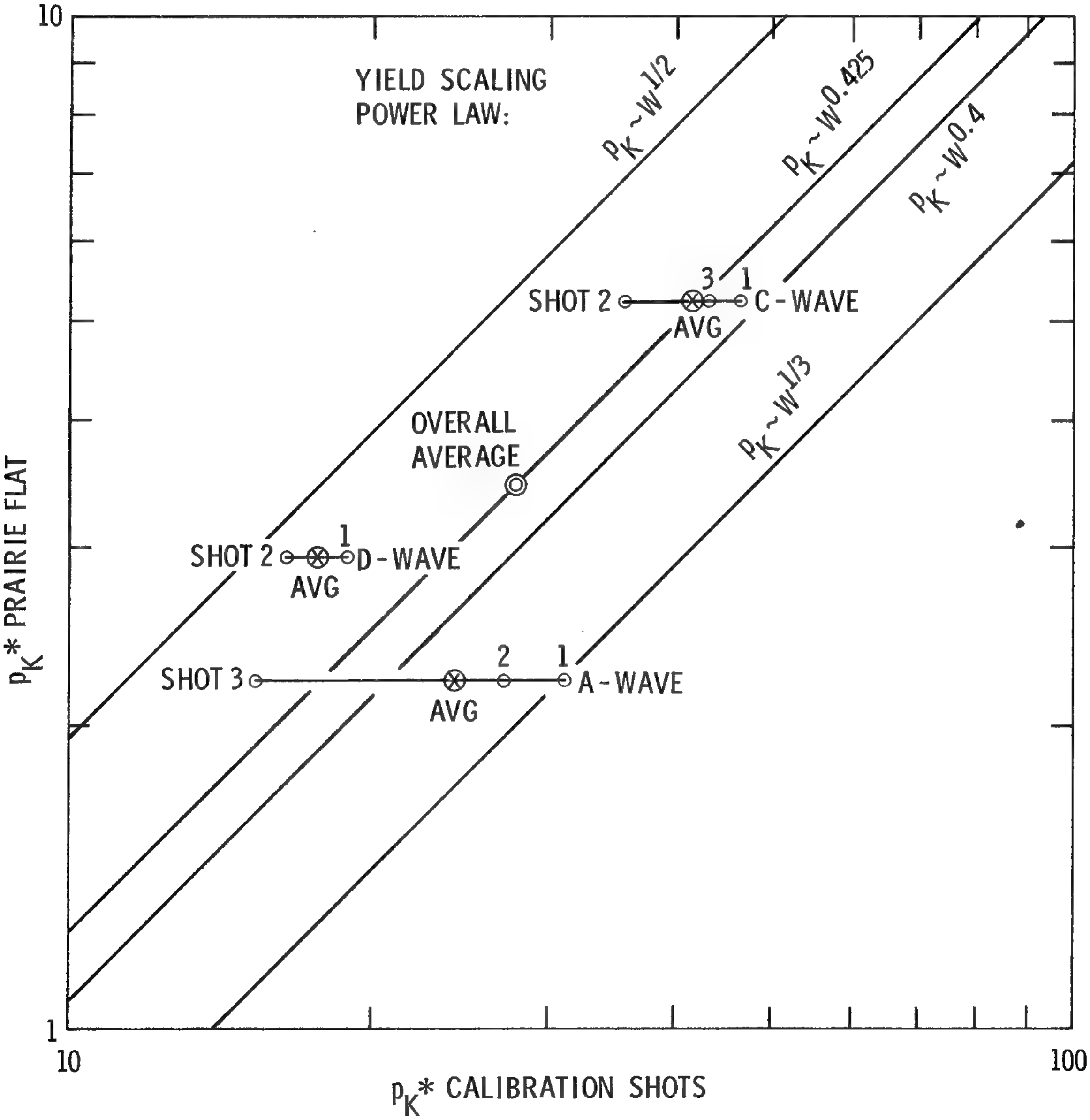

Figure 28. Comparison of PRAIRIE FLAT and Calibration Shot Average Peak Amplitudes

Conclusions

Successful microbarograph records were obtained from 18 stations, at 1- and 2-mile spacings, on an east-west line centered 130 miles west from PRAIRIE FLAT. Each station recorded waves from PRAIRIE FLAT and the three 1.2-ton HE calibration shots fired at Z -30, Z -15, and Z +15 minutes.

Balloon rawinsonde and Arcas rocketsonde wind and temperature measurements were collected and these allowed ray calculations and predictions for signal propagation. Comparison of calculations and measurements showed that some further detailed structure to the atmospheric structure must be assumed to give the various wave groups, arrival times, and incidence angles (phase velocities) which were recorded. Recorded amplitudes from calibration shots averaged smaller than the ray calculation predicted, but some stations got amplitudes comparable to the main wave prediction.

Recordings at Pullman, Washington, of calibration shots were too small to be clearly seen above ambient noise. Three P-F signals were quite clear and arrived at reasonable times, but the reported amplitudes are a factor of 10 smaller than expected and there is some doubt about the correct recorded sensitivity.

There were bumps in the amplitude-versus-distance curve which were observed to pass through the array and change from shot to shot. These appear to be the caustic, which was broken up by atmospheric irregularities, and gave about doubled amplitudes over 6- to 8-mile bands. Statistical analyses showed that this short time-scale variability and station-to-station variations were not so large as had been previously recorded from measurements in a sound duct from lower altitude jet-stream winds in Nevada. Also station-to-station variability was smaller for PRAIRIE FLAT waves of larger yield, lower frequency and longer wavelength. This was expected for the longer wavelengths, and they appeared to have been relatively unaffected by some of the smaller scale atmospheric turbulence which affected calibration shots.

Comparison of averaged amplitudes for the two yields showed that amplitude was proportional to the 0.425 power of apparent blast yield, close to the 0.40 value which was previously measured.

REFERENCES

1. Keefer, J. H., F. M. Sauer, and C. J. Cauthen, Jr., Operation PRAIRIE FLAT, Technical and Administrative Information for U.S. Programs, DASIAC Special Report 69, Hq. DASA, GE-TEMPO, Santa Barbara, California, 15 May 1968.

2. Reed, J. W., Explosion Wave Amplitudes Statistics for a Caustic at Ranges of 30 to 45 Miles, SC-RR-67-680, Sandia Corporation, Albuquerque, New Mexico, February 1968.

3. Broyles, C. D., IBM Problem M Curves, SC-TM-268-56(51), Sandia Corporation, Albuquerque, New Mexico, December 1, 1956.

4. Reed, J. W., "Amplitude Variability of Explosion Waves at Long Ranges," J. Acoust. Soc. of Amer., Vol 39, No. 5, Pt. 1, May 1966.

5. Maxim, J. A., Reed, J. W., and Shoemaker, F., Microbarograph Operations Manual, SC-4942(M), Sandia Corporation, Albuquerque, New Mexico, June 1964.

6. Bodhaine, B. A., Wind Attenuators for Microbarograph Measurements, SC-TM-65-469, Sandia Corporation, Albuquerque, New Mexico, October 1965.

7. Unpublished Communication, O. Johnson, DRES, to J. W. Reed, Sandia Corporation, Subject: "Temperature and Wind Profiles PRAIRIE FLAT," 21 August 1968.

8. Cox, E. F., "Sound Propagation in Air," Handbuch der Physik, Vol 48, Chapter 22, Springer-Verlag, Berlin, 1958.

9. Cox, E. F., Plagge, H. F., and Reed, J. W., "Meteorology Directs Where Blast Will Strike," Bull. Am. Meteorol. Soc. Vol 35, No. 3, pp. 95-103, March 1954.

10. Thompson, R. J., Computing Sound Rays in the Presence of Wind, SC-RR-67-53, Sandia Corporation, Albuquerque, New Mexico, February 1967.

11. Vortman, L. J. and Shreve, J. D., The Effect of Height of Explosion on Blast Parameters, SC-3858, Sandia Corporation, Albuquerque, New Mexico, June 20, 1956.

12. Kelso, J. R., Stalk, G., and Clifford, C. C., Project Banshee Field Operations, 1961 and 1962; Preliminary Report, DASA-543, DASA, May 1963.

13. Unpublished Communication, J. Thomas to J. W. Reed, Subject: "PRAIRIE FLAT Data," 15 August 1968

14. (P-F Preliminary Report).

15. Crary, A. P., "Stratosphere Winds and Temperatures from Acoustical Propagation Studies," J. of Meteor., Vol 7, pp. 233-242, 1950.

16. Johnson, C. T. and Hale, F. E., "Abnormal Sound Propagation over the Southwestern United States," J. Acoust. Soc. Amer., Vol 25, pp. 642-650, July 1953.

17. Reed, J. W., Ozonospheric Observations from Propagation of Atomic Blast Waves, SCTM 86-55(51), Sandia Corporation, June 1, 1955.

18. Reed, J. W., An Approach to Damage Estimation Near Calculated Caustics, SC-RR-68-870, Sandia Corporation, February 1968.

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